DYNAMIC SYSTEM MODELING AND DECISION SUPPORT FOR GROW-FINISH SWINE BARN OPERATION

BY

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DISSERTATION

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ABSTRACT

Understanding both swine growth performance and swine barn management under different conditions is essential to evaluate the swine production system. The integrated effect of swine growth and swine barn management is difficult to investigate because of their complex relationships. To estimate the integrated effect between swine growth and swine barn management, a dynamic modeling approach is proposed and applied to simulate swine growth performance under different swine barn management practices.

To better simulate the swine growth performance, a modified simple pig growth model (MSPGM) was developed, calibrated, and validated based on two recent separate experiments conducted in 2016 with the same breeding line of swine but different indoor temperatures. The calibration results of the MSPGM demonstrate that swine in the experiment grow leaner, consume more feed, have higher maximum protein deposition rate, and utilize energy more efficiently to deposit body lipid and protein, as compared to data obtained from previous studies. The validation results under lower indoor temperature of the MSPGM showed an underestimation of pig weight, feed intake, and backfat probe thickness with the current modeling scheme.

Based on the MSPGM, a process-level integrated swine production system model (ISPSM) was developed by incorporating a grow-finish (33 kg – 130 kg) swine growth simulation with a mechanical-ventilated swine barn management system. A sensitivity analysis on specific ISPSM parameters was then conducted to identify critical swine production practices on different production and performance indicators, including the average daily gain (ADG), feed conversion ratio (FCR), total utility cost (TUC), and marginal utility cost (MUC) for the growing cycle. A case study in Ames, Iowa, was conducted for sensitivity analysis of both heating (Jan - Mar) and cooling seasons (May - Oct) in 2013 to evaluate the potential integrated effect on a virtual 2400-

head mechanical-ventilated grow-finish swine barn. Under the ISPSM, the minimum body lipid to protein ratio, building setpoint temperature, and protein level in the diet were shown to be the three most influential parameters on the swine performance indicators. Leaner swine performed better for all performance indicators. A higher setpoint temperature tended to decrease the ADG during both seasons but increased the FCR during the heating season. Both low and high protein levels in feed tended to have a negative impact on the FCR, which implies the existence of an optimum protein level in the diet. During the cooling season, the results indicated that lower protein levels in the diet affected a higher FCR, as compared to the heating season. This modeling result implies the importance of maintaining a sufficient protein level in the diet, especially when swine consume less feed during the cooling season.

While seasonality has an important effect on swine growth performance, heat stress in the cooling season can be improved by implementing evaporative cooling as a part of the ventilation system. Although several studies have suggested different evaporative cooling pad (ECP) control approaches based on environmental variables that include temperature, relative humidity, and indices such as thermal humidity index, few studies have been published on the swine barn economic returns of ECP operation strategies. The current research applied the ISPSM to evaluate the economic return for different ECP control offsets for a virtual swine barn. The average daily gain (ADG), daily total utility cost (TUC), marginal utility cost (MUC), evaporative operation cost, and feed conversion ratio (FCR) were used as factors to evaluate the average daily profit (ADP) for the entire growing cycle. A comparison among potential savings due to different ECP control offsets for the cooling season was estimated based on an Iowa virtual swine barn case study using weather data for the past 18 years. Among the different scenarios, **no** statistically significant differences were found for the FCR. However, statistically significant differences for the AEUC, MUC, ADG, and ADP were found between scenarios with lower and higher ECP operating temperature offsets. This research also found a larger deviation for ADP when ECP operated both at a higher temperature offset and without an ECP operation, which implies the potential benefit of operating an ECP at a lower temperature offset. On the other hand, the simulation result implies that contract growers who focus more on the MUC would likely not choose to operate the cooling pad based on the assumed conditions.

Current grow-finish swine producers follow a setpoint temperature by operating under recommendations to reduce the growing period based on the swine live weight without considering the outdoor environment. To meet the difficult-to-achieve setpoint temperature based on those recommendations, the swine house requires extensive energy input. As a result, a more comprehensive setpoint temperature recommendation is required to optimize the economic return of swine housing operation. Based on the ISPSM, the current research developed an economic optimization procedure by recommending daily a setpoint temperature for grow-finish swine production that takes into consideration forecasted outdoor temperature and estimated economic returns. Different economic perspectives were investigated to 1) minimize the FCR for integrated producers, 2) minimize the MUC for contract growers, and 3) optimize the overall economic returns for independent producers. A case study using a virtual swine production system in 2013 located in Ames, Iowa, with different perspectives was conducted to evaluate the optimization procedure. The results showed a higher setpoint temperature in the cooling season and a longer growing period from the contractors' perspective. In order to produce revenue, integrators and independent producers tend to meet the setpoint with a lower temperature to create the best FCR and ADG. While the optimized setpoint temperature profiles are similar with or without the ECP operation, the setpoint for optimum FCR and ADP tends to be higher for scenarios without ECP, due to the difficulties to achieve LCT.

To my wife, Haozheng Jiang, and to my parents, Yuan-Jung Yang and Shu-Te Shih

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NOMENCLATURE

A	animal activity
ADG	average daily gain, kg d^{-1}
ADP	average daily profit, \$ d^{-1}
$AEUC$	average energy utility cost, \$
a	Constant of metabolizable energy estimation
BF_i^D	denotes observed backfat probe thickness for i^{th} pig at time D
$\boldsymbol{\widehat{BF}_\iota}$	denotes simulated backfat probe thickness time series vector for ith pig
$\widehat{BF}_i^D$	simulated backfat probe thickness for i^{th} pig at time D, and is an element of $\boldsymbol{\widehat{BF}_\iota}$
$Bleach\$$	cost for commercial available chlorine-based bleach, \$ $ounce^{-1}$
b	Constant of metabolizable energy estimation
C_{ele}^D	electricity cost at day D, \$
$\hat{C}_{ele}^D$	predicted electricity cost at day D, \$
C_{fuel}^D	fuel cost at day D, \$
$\hat{C}_{fuel}^D$	predicted fuel cost at day D, \$
C_f	fuel price per m^3 , \$ m^{-3}
C_e	electricity price per kwh, \$ kWh^{-1}
C_p	heat capacity of air, j kg^{-1} $°C^{-1}$
CFI_i^t	denotes observed cumulative feed intake for i^{th} pig at time t
$\boldsymbol{\widehat{CFI}_i}$	simulated cumulative feed intake time series vector for i^{th} pig
$\widehat{CFI}_i^t$	simulated cumulative feed intake for i^{th} pig at time t, and is an element of $\boldsymbol{\widehat{CFI}_i}$
CO_{ECP}	control offset of the evaporative cooling pad, °C
$\boldsymbol{CS_V}$	control stages for ventilation, °C
$\boldsymbol{CS_H}$	control stages of heating, °C
c	Constant of metabolizable energy estimation
DC	depreciation cost for cooling pad, \$ day^{-1}
$Disinfectants_{op}$	disinfectants cost for operation, \$ m^{-3}
ECP	evaporative cooling pad
Em	maintenance energy, kJ d^{-1}
Eld	energy requirements on lipid deposition, kJ g^{-1}
Epd	energy requirements on protein deposition, kJ g^{-1}
$E_{op}C$	evaporative cooling pad operational cost, \$ m^{-3}
FC	feed cost, \$
FCR	feed conversion ratio, kg kg^{-1}
FI^D	feed intake at day D, kg
$\widehat{FI}^D$	predicted feed intake at day D, kg
$\boldsymbol{f_{MSPGM}}$	modified simple pig growth model (MSPGM)
$\boldsymbol{f_{ISPSM}}$	integrated swine production model (ISPSM) developed in Chapter 4
HCT	higher critical temperature, °C
$HV_{natural\ gas}$	heating value of natural gas, J m^{-3}

h	current hour of the day (24 hour clock)
h_{min}	hours that the minimum activity occurs
$InitialLP$	initial lipid to protein ratio, kg kg^{-1}
k	total number of observation for backfat probe thickness
LCT	low critical temperature, °C
l_{cycle}	length of growing period, d
m	total number of observation for live weight and feed intake
M_{FI}	modification factor for feed intake
$MEvi$	metabolizeble energy intake, kJ d^{-1}
MUC	marginal utility cost (AEUC/ADG), \$ kg^{-1}
$minLP$	minimum lipid to protein ratio, kg kg^{-1}
N	number of swine in a barn
n	number of swine on experiment
Pd_{max}	maximum protein deposition rate, g day^{-1}
P_F	power consumption of ventilation fan, W
P_L	power consumption for light, W
$Pad\$$	cost for evaporative cooling pad, \$ m^{-2}
$PadA$	area of evaporative cooling pad, m^2
$Pig\$$	pork price, (\$ kg^{-1})
q_B	the heat loss through building envelope, W
q_F	the heat loss through ventilation fans, W
q_H	the heat generated by fuel heaters, W
$\boldsymbol{q_{HS}}$	the heat generated by fuel heaters corresponding to heating stages, W
q_p	total sensible heat generated by pigs, W
$rAPd$	ratio to referenced available protein in diet, %
$\boldsymbol{rH_o}$	outdoor relative humidity, %
rH_o^D	outdoor relative humidity at day D, %
$\widehat{rH}_o^D$	predicted outdoor relative humidity at day D, %
rPd_{max}	ratio to referenced maximum daily protein deposition rate
$Sump\$$	price for Sump, \$
Tc	cooled inlet temperature, °C
T_e	evaporated temperature, °C
T_i	indoor temperature, °C
T_i^C	critical daily indoor temperature, assumed to be daily T_i, °C
T_{inlet}	inlet temperature, °C
$T_{i,l}$	the indoor temperature at distance l from the cooling pad, °C
$\boldsymbol{T_o}$	outdoor temperature, °C
T_o^D	outdoor temperature at day D, °C
$\hat{T}_o^D$	predicted outdoor temperature at day D, °C
$\boldsymbol{T_s}$	setpoint temperature, °C
T_{set}^D	potential setpoint temperature at day D, °C
$\bar{T}_{set}^{D+1}$	optimum setpoint temperature at time D, °C
T_w	wet bulb temperature, °C
THI	Thermal humidity index

TSI	total sensitivity index
U_E	electricity utility cost, $
U_G	gas utility cost, $
UA	heat conductance of building envelope, w °C^{-1}
V_i	variance of ith parameter
$\dot{V}$	ventilation rate for corresponding stages, m^3 s^{-1}
V	volume of the barn, m^3
Ve	face velocity of ventilation inlet, m s^{-1}
$\boldsymbol{VER}$	fan efficiency, m^3 s^{-1} W
V_{total}	total variance
W	Live weight of the pig, kg
W_0	initial weight of the pig, kg
W_{op}	water loss due to operation, kg d^{-1}
W_i^0	denotes initial weight for *ith* pig
W^D	denotes the real live weight for one pig at time D
W_i^D	denotes observed weight for *ith* pig at time *D*
$\widehat{W}^D$	predicted weight of the pig at day D, kg
$\widehat{\boldsymbol{W}_\iota}$	simulated weight time series vector for *ith* pig
$\widehat{W}_i^D$	denotes simulated weight for *ith* pig at time *D*, and is an element of $\widehat{\boldsymbol{W}_\iota}$
Z^D	updated objective function outcome at time D
$\hat{Z}^D$	predicted objective function outcome at time D
Φ_{tot}	total heat production at 20°C, W
Φ_{tot}^*	modified total heat production at temperature different to 20°C, W
Φ_{sen}^*	sensible heat production, W
$\rho_{\bar{a}}$	air density, kg m^{-3}
η_s	cooling pad saturation efficiency, %

CHAPTER 1: INTRODUCTION

1.1 Justification for Research

To meet the expanding global demand for pork and to increase profit margins, the swine industry for decades has been shifting from small farmers to large-scale operations, complete with mechanized facilities. Modern commercial swine operations have improved swine breeds, provided balanced feed ingredients, and moved the swine barn environment from natural ventilation to mechanical ventilation with cooling and heating units implemented to control the indoor environment.

Commercial grow-finish swine facilities that are mechanically-ventilated raise pigs from small size to market size in the same room that require dynamic environmental conditions and complex swine barn operations. Most existing swine barns currently control the indoor environment by operating the ventilation fan and heaters based on a setpoint temperature that aims to provide a comfortable environment for swine and a shorter growing period. However, a satisfactory setpoint is often unachievable due to hot and humid outdoor climate conditions that lead to seasonality differences in swine production performance. Moreover, to meet a specific setpoint temperature under particular outdoor climate conditions, requires that the swine barn utilizes high energy. To meet the challenges of seasonal differences in swine production, the potential for controlling swine growth depends on a more comprehensive swine barn operation.

Researchers have developed computational models to estimate swine growth performance under conditions of different feed ingredients and growing environments. Based on extensive experimental results, different nutrient partitioning schemes have been designed to describe swine growth under various conditions. In the 1980s, Black et al. (1987) developed a model (AUSPIG) to simulate the entire growing cycle that included predictions of the *ad libitum* effects of nutrition, genetics, and environment. Later in the 1990s, researchers (Bridges, Turner, Stahly, Usry, & Loewer, 1992; Bridges, Turner, Usry, & Nienaber, 1992; Usry, Turner, Bridges, & Nienaber, 1992) in the U.S. developed a model (NCPIG) and then combined that model with a natural ventilated system to evaluate the economics for introducing a mist cooling system (Turner et a., 1998). In the 2000s, researchers (Green and Whittemore, 2003; Green and Whittemore, 2005) in Europe built a comprehensive model (IMS Pig) based on a novel nutrient partitioning scheme. Through use of image processing technology, Parsons et al. (2007) were capable of controlling pig growth by optimizing dietary blends. While these comprehensive models were useful in providing accurate predictions, they were too complicated for producers to apply. Specifically, the models needed to implement a complicated calibration process. Furthermore, few of the studies considered large-scale swine growth performance under different swine barn operation strategies that involve mechanically-ventilated grow-finish swine barns. Moreover, most of the swine models were developed more than ten years ago and are not designed to evaluate modern swine growth performance in which the industry prefers faster and leaner growth with greater feed consumption.

Despite the weaknesses of those models, numerous research studies have been published regarding mechanically-ventilated grow-finish swine barn operation strategies that focus on different swine sizes and ingredients. Strategies for heating and ventilation systems in swine housing have been simulated by many researchers. Lambert et al. (2001) compared different kinds of control systems by assuming linear pig growth performance inside the barn. Morsing et al. (2005) also simulated indoor psychrometric properties and swine barn energy consumption according to swine heat and moisture production based on Danish recommendations for growing pigs. While these studies provided insights into different types of swine barn management, they did not take into consideration pig growth performance relative to the swine barn indoor environment.

The growing environment affects not only feed intake and pig growth but swine production performance also affects the swine barn. So far, the relationship between swine barn operation and swine production performance has drawn scant research attention and is still not well understood. In order to investigate the integrated effects of barn operation on swine growth performance, it is necessary to examine how those variables are interrelated. Based on the existing models of both swine growth and swine barn operation, the current study proposes a system model to investigate the interrelationships.

Multiple benefits accrue for the use of system modeling and analytics to support decision-making of the swine barn operation. In particular, (1) lower costs to investigate, evaluate, and optimize swine barn operations compared to extensive experiments that are currently required; and (2) predictions for precise swine barn operation based on lower information requirements. Because the complex system model proposed by the current study integrates different types of information, it can calibrate some of the parameters, such as energy required for lipid/ protein deposition simply by pig weight, feed intake, and backfat probe thickness observation.

1.2 Objectives

The overall goal of this research is to investigate the relationship between modern grow-finish swine production performance and different types of mechanically-ventilated swine barn operations by using system modeling analytics. In order to achieve this goal, the specific objectives are as follows:

1) To develop, calibrate, and validate a model for modern swine growth performance
2) To develop a process-based swine barn – swine growth dynamic system model.
3) To investigate integrated relationships between swine growth performance and swine barn management.

4) To evaluate evaporative cooling pad control offsets based on the proposed dynamic system model.
5) To investigate optimum daily setpoint temperatures for different swine production performance based on the proposed dynamic system model.

1.3 Dissertation Organization

This dissertation is organized into seven chapters. Chapter 1 includes the introduction and research objectives. A review of the literature on swine barn management, grow-finish swine growth under different conditions, and swine growth models is presented in Chapter 2. A swine growth model calibration-validation for use in evaluating swine growth performance is presented in Chapter 3. Based on the calibrated swine growth model, a dynamic system model is developed in Chapter 4, including a sensitivity analysis of the model for investigating integrated relationships of the swine barn operation and swine growth performance. The model is then expanded and applied to evaluate evaporative cooling pad control offsets for swine barns (Chapter 5). Based on the proposed dynamic model, optimum setpoint temperature with a cooling pad operation for different types of producers is described for different types of producers in Chapter 6. An overall summary of this dissertation research and recommendations for future work are addressed in Chapter 7.

CHAPTER 2: LITERATURE REVIEW

Swine production is highly correlated with nutrient intake and the surrounding environment of facilities in which the swine are housed. In turn, swine barn environment control strategies depend on swine production status. Due to these inner-locking variables, there is a need to understand the dynamic relationships that exist between the swine barn operation and swine growth inside the barn.

This chapter summarizes previous research studies on swine production performance under different temperature and humidity conditions, followed by a review of computational swine growth models. A review of research on swine barn modeling and operation strategies under various conditions follows. In conclusion, a summary of the literature is discussed.

The research described here serves as the basis for the dynamic swine barn and swine production system model proposed by the current study and provides a baseline for discussions about swine barn operation.

2.1 Swine Production Performance under Different Environmental Conditions

The swine growing environment is shown to influence swine production performance. To understand the potential effects of swine barn indoor environments on swine production performance, this section focuses on experimental research results related to swine production performance relative to different types of indoor environments.

2.1.1 Swine growth performance with regard to temperature

While swine barns adopt different types of facilities to control a proper indoor temperature, low indoor setpoint is still not achievable when the outdoor temperature and humidity are high during the cooling season. Therefore, the seasonal differences of swine growth production, caused mainly by the outdoor environment, can be observed as variations in the indoor environment. Meanwhile, past experiments that focused on seasonality can serve as examples that demonstrate swine growth under different indoor temperatures.

In 1949, Heitman and Hughes conducted an experiment to examine the effect of temperature and relative humidity levels on swine physiological responses. In their experiment, Heitman and Huges observed best temperature ranges for different sizes of swine as measured by the highest rate of gain and the lowest feed conversion ratio. The best temperature range was then further validated by other research groups.

Hale et al. (1968) conducted an experiment on swine performance and carcass characteristics during different seasons relative to gender and dietary energy intake. Results of their study conducted during the winter showed higher feed to gain ratio in which the swine were fatter during the winter months compared to the summer months. Hale et al. observed that the barrows consumed more feed, had higher fat content in the carcass, and had a higher feed to gain ratio than the gilts. Their study also showed a decrease in feed requirements accompanied by a higher energy content. The experiment conducted by Hale et al. (1968) served as the basis for future model development. More recently, Schinckel et al. (2012) update the Bridge's function for different types of swine and assumed a constant metabolizable energy intake to further describe the adverse relationships between feed intake requirements and feed energy content.

Regarding swine growth that was observed to fluctuate with indoor temperature, a later study by Hahn et al. (1987) reviewed experiments related to air temperature influence on swine production performance. Results of that study suggested that a daily temperature cycle of up to 5°C to 8°C relative to the mean temperature caused no adverse effects on an *ad-libitum* diet. Moreover, their research also showed that the best feed conversion ratio was in the group with higher indoor temperature, but the feed conversion ratio increased at a specific higher temperature. Their findings demonstrate that there exists an optimum indoor temperature range for feed conversion ratio and suggests the importance of average indoor temperature on swine growth performance under *ad libitum* conditions.

Lopez et al. published two studies (Lopez et al., 1991a, Lopez et al., 1991b) regarding the effects of temperature on finishing swine performance in both cooling and heating seasons. In the cooling season, they observed a higher feed intake and average daily gain with a hot, diurnal temperature (22.5°C to 35°C) compared to a constant thermoneutral temperature (20°C). No differences were observed for feed efficiency. In the heating season, Lopez et al. also compared a cold diurnal temperature (-5°C to 8°C) and thermoneutral temperature environment. The cold diurnal scenario demonstrated a lower average daily gain and a higher feed intake that led to a higher feed conversion ratio. Results of their study showed lower production performance at both high diurnal temperature and cold diurnal temperature as well as the need to keep the indoor temperature in the thermal neutral zone to prevent production losses and a higher feed conversion ratio.

Christon (1998) conducted experiments to evaluate differences in the environmental effect (tropical region and thermalneutral) and feeding methods (*ad lib* and restricted). Their experiment showed no statistical differences in body composition, but there was a decrease in growth rate and feed efficiency in the tropical region compared to efficiency in thermalneutral condition. The feeding method showed no statistical significance in feed conversion efficiency, but results for the tropical trial restricted feeding method had a higher feed conversion ratio than the feed conversion ratio in *ad-lib* diets.

Myer et al. (1998) conducted an experiment that compared swine growth performance in both summer and fall reared condition with various dietary lysine levels. The fall season experiment results demonstrated a lower feed conversion ratio than experiment results in the summer. The same research group conducted similar research ten years later. Myer et al. (2008) conducted a two-year experiment on finishing swine and evaluated swine production performance and carcass lean content with corn-SBM diets. The results of their later study demonstrated that seasonality has a significant influence on both average daily gain and feed conversion ratio. Winter has a higher average daily gain and a higher feed conversion ratio compared to summer. However, the carcass lean was not affected by seasons in their experiment. While both experiments had a similar setup, the research results on feed conversion ratio from Myer et al. (1998) and Myer et al. (2008) were contradictory. The main reason might be the improvement of biological potential for growth.

White et al. (2008) conducted experiments on grow-finish swine with heat stress (indoor temperature at 32.2°C) and at different stock densities. Their results also demonstrated a lower average daily gain but a higher feed conversion ratio under temperature stress and at higher stock densities. While the experiment conducted by Myer et al. (2008) showed no effect of seasonality on carcass lean, White et al. (2008) observed leaner and lower saturated lipid bacon under temperature stress. The main difference between results of these two experiments may be attributed to differences in management in the cooling season. While White et al. (2008) analyzed grow-finish pigs under heat stress, Myer et al. (2008) cooled down the indoor temperature by sprinkling water when the indoor temperature exceeded 25C. Moreover, White et al. (2008) and Myer et al. (2008) used different crude protein levels in the experiment diet. Results from research conducted by Myer et al. (2008) and White et al. (2008) serve as a baseline for future model discussions on seasonality.

Lewis and Bunter (2011) conducted experiments in Australia to compare the seasonality effect of ambient temperature on production performance. In winter, the average daily gain, feed intake, and feed conversion ratio, were shown to be larger than in the summer. Their results demonstrated that the temperature is influential on swine phenotypic outcomes.

More recently, Renaudeau et al. (2014) conducted meta-data analysis to analyze published studies related to ambient temperature and swine growth. Their results showed decreases in both average daily gain and average feed intake under higher indoor temperature. The feed conversion ratio, however, did not indicate a clear tendency with regard to temperature. Using multi-variable regression, Renaudeau et al. (2014) predicted the feed conversion ratio and drew relationships between ambient temperature and feed conversion ratio and showed a convex function regarding indoor temperature. Although the convex function did not show a significant trend with regard to heat stress, it did demonstrate the existence of a best feed conversion efficiency that serves as a baseline for further discussion.

While previous research has produced consistent experiment results regarding the effects of indoor temperature on feed intake and daily gain, there are no consistent research results with regard to the feed conversion ratio as shown in Table 2.1. In the cooling season, some researchers observed a higher feed conversion ratio while others observed the opposite. To better understand the seasonality effect on the feed conversion ratio as well as to analyze the reasons for the mechanism that underlies the inconsistent outcomes, it is necessary to examine other factors by setting up yet another experiment design that investigates, for example, diet ingredients, artificial cooling, and swine biological growth potential.

Table 2.1 Qualitative summary of swine production performance in different seasons. * denotes the higher number in the category. ** denotes statistically higher value for that category						
Reference	Average Daily Gain (kg)		Feed Intake (kg)		Feed Conversion Ratio (kg feed/ kg gain)	
	Summer (heat stress)	Thermalneutral (Winter/Fall)	Summer (heat stress)	Thermalneutral (Winter/Fall)	Summer (heat stress)	Thermalneutral (Winter/Fall)
Heitman and Huges (1949)		*		*	*	
Hale et al. (1968)		*		**		**
Hahn et al. (1987)		*		*	*	
Christon (1988)		**		*	**	
Lopez et al. (1991)		**		**	*	
Myer et al. (1998)		**		**	**	
Myer et al. (2008)		**		**		**
White et al. (2008)		**		**	**	
Lewis and Bunter (2011)		**		**		**
Renaudeau et al. (2014)		*		*	NA	NA

2.1.2 Swine growth performance with regard to humidity

In addition to fluctuations in indoor temperature in different seasons, the effects of indoor humidity have been studied relative to swine growth performance. Heitman and Hughes (1949) conducted experiments that vary the humidity level from 30% to 94% at 96 °F to demonstrate the effects of humidity on swine physiological responses. Respiration rates and body temperature were observed to increase rapidly. The results from a study by Heitman and Hughes (1949) implies that a larger energy expense is needed to maintain a higher body temperature.

While high humidity and temperature may decrease swine comfort level and affect voluntary feed intake, humidity along with optimum indoor temperature does not have a direct effect on production performance (Morrison et al., 1966). Two years later, Morrison et al. (1968) reviewed the growth condition with different humidity levels at higher ambient temperature conditions. Their findings showed that swine weight gain is lower under high humidity at the same temperature greater than 72 °F. Those results demonstrate that humidity is more influential in the cooling season compared to the heating season.

Based on the swine physiological response to both different temperature and humidity levels, additional research has estimated effective temperatures with regard to various humidity levels (Morrison et al., 1968; Homes & Close, 1977) and found that an effective ambient temperature is estimated to be:

$$EAT = 0.35 \times T_{wb} + 0.65 \times T_{db} \tag{2.1}$$

Because the pig is a non-sweating species, the dry bulb temperature has a higher weighting in estimating the EAT.

In order to consider both temperature and humidity effects on swine comfort. Roller and Goldman (1969) created the thermal-humidity index (THI) for swine. The THI has been further applied to evaluate the indoor environment in several swine barn operation studies. Subsequently, Panagakis et al. (1991) defined heat stress for swine indoor environment by the duration that exceeds upper critical temperature and the intensity of the exceeded indoor temperature. A year later, Axaopoulos et al. (1992) discussed the grow-finish swine barn indoor environment based on constant 50 kg swine and heat intensity. Their research concludes that in summer ventilation alone cannot prevent heat stress based on heat intensity. They also suggested that the thermal-humidity index (THI) is not the most appropriate index for indoor comfort environment in Greece.

2.2 Swine Growth Model

While experimental results have provided solid evidence on swine growth relative to different environmental conditions, some of the inter-relationships between environment, diet, and genotype have still not been thoroughly investigated based on an integrated experimental design. Rather, in efforts to understand the integrated effects, researchers have developed different types of nutrient partitioning schemes to simulate the pig growth process. From early stages of this line of research, simple integration of empirical relationships based on various modeling schemes have evolved to simulate detailed nutrient mechanisms. While complex models provide more insight into nutrient partitioning and energy utilization mechanisms, their models require more information for model calibration that is difficult for commercial swine barn to provide.

In 1976, C. Whittemore and Fawcett developed a preliminary pig nutrient partitioning model by demonstrating substantial empirical relationships between different parameters. Whittemore (1986) suggested that pig growth models should remain flexible, allowing for effective forward prediction. His later article addressed the importance of testing ideas based on the use of models and understanding, rather than merely measuring, the growth response.

Black et al. (1987) developed a model (AUSPIG) that simulates the entire growing cycle and includes predictions of the *ad libitum* effect. Black's model used nutrition, genetics, and environment as input variables for development of a deterministic model of swine intake and growth. Today, the AUSPIG model is still widely applied in academic and commercial practices.

In the same year, Moughan et al. (1987) developed a simple pig growth model for the growing-finishing period of swine production to describe pig live weight changes on a daily basis. Unlike Black et al. (1987) who examined empirical relationships between parameters to determine nitrogen retention, Moughan constrained body protein retention by requiring a minimum level of body lipid. Moughan's model showed moderate predictions with few parameters. Although that model did not take into account environmental factors and assumed pig growth under the thermoneutral conditions, the simplicity and elegance of that modeling scheme has been widely applied to other models. The Moughan model was created 30 years ago, yet the NRC (2012) continues to update several empirical relationships that can be applied to the Moughan model scheme, including the relationship between pig feed intake and indoor temperature. The updated empirical equations from NRC (2012) can be used to expand the simple pig growth model with regard to pig growing outside the thermalneutral zone.

Subsequently, researchers in the U.S. developed a model (NCPIG) based on the interaction of environmental factors, feed intake, and genotypes. That model also predicted how *ad libitum* intake influences pig growth (Bridges, Turner, Stahly, Usry, & Loewer, 1992; Bridges, Turner, Usry, & Nienaber, 1992; Usry, Turner, Bridges, & Nienaber, 1992). Based on simulated heat production as well as core body temperature, the feed intake and blood nutrient level were then estimated. All nutrient partitioning were further simulated based on the level of nutrients in the blood. The NCPIG model provided more accurate results compared to experimental results; however, the full NCPIG model is difficult to use due to its complicated parameters. Three years later, in order to avoid those difficulties, Bridges et al. (1995) built a neural network model based on the NCPIG model that simplified parameters and computation processes.

More recently, researchers in Europe developed a model (IMS PIG) based on a novel nutrient scheme and modeling architecture that provide variable nutrient absorption efficiency (Green and Whittemore, 2003). That model takes into account the fact that energy requirements for pig growth and maintenance are all based on ATP, which is delivered with different efficiencies depending on different energy sources. The IMS PIG model calibrated three different major types of breeding lines based on swine serially slaughtered from 25 kg to 115 kg (Green and Whittemore, 2005). Researchers further used an optimization approach to update models in real time as wells as to control the feed ingredients for target swine body composition (Parsons et al., 2007). Green and Whittemore's comprehensive model and integrated management system (IMS) demonstrated an excellent opportunity to apply advanced ingredient control; however, the research was conducted at a controlled constant indoor ambient temperature and did not consider the unachievable setpoint and the corresponding seasonality effect for commercial swine barn operations.

In order to achieve a more accurate voluntary feed intake estimation, Yoosuk et al. (2011) combined different models and developed a simulator focused on voluntary feed intake predictions. Their model adopted Roan (1991)'s model scheme that considered feed intake based on energy requirements. Specifically, when the temperature is high, the swine energy expense will decrease and hence decrease the feed intake. However, when the energy expense increases in winter, the swine will consume more feed to generate the extra energy required in a cold environment. Based on NRC (1998), Yoosuk's model also takes stocking density as an input to modify the total feed intake. In addition to models developed by Roan (1991) and Yoosuk et al. (2011) models, Schinckel et al. (2012) has suggested an empirical relationship between feed intake and indoor temperature. The swine feed intake will decrease when the temperature exceeds the thermoneutral zone. By contrast, the swine feed intake will increase when the temperature is lower than the lower critical temperature. Due to better growth performances, the NRC (2012) also modified several empirical equations with regard to the nutrient partitioning scheme.

2.3. Swine Barn Thermal Model

The swine barn indoor environment can be simulated based on the 1) thermal characteristics of the barn, 2) the heat-moisture production from the swine, and 3) indoor control systems, such as ventilation fans and heating units, and corresponding control thresholds.

Albright (1990) demonstrated a steady state estimation for the swine barn indoor environment and to estimate the heating and cooling load, assumed that the indoor temperature and humidity are equal to the setpoint. While Albright's approach provides for a quick estimation, it is not always correct due to unachievable setpoint temperature during summer. In order to discuss the swine barn transient indoor environment behavior, Axaopoulos et al. (1992) simulated the thermal microenvironment of growing. Their simulation considered time-dependent equations related not only to swine moisture production but also to manure water vapor production. Two years later, Axaopoulos et al. (1994) developed a model (AGRISIM) to simulate the swine barn indoor environment dynamically with a *constant* pig weight between 20 kg to 100 kg swine. The model simulated only a fraction of dynamic indoor temperature but did not consider the interaction between pig growth and swine barn environment. Chao et al. (2000) also built a lumped variable dynamic model to discuss the difference between a stage controller and a fuzzy-logic controller. Panagakis and Axaopoulos (2006) further applied the lump variable dynamic model approach to simulated indoor temperature and humidity with a comparison of evaporative cooling pads and fogging methods. In general, the mechanically-ventilated swine barn dynamic thermal model can be described as follows:

$$\rho_{\bar{a}} C_P V \frac{dT_i}{dt} = (q_p + q_H - q_B - q_F) \tag{2.2}$$

where q_p (W) is the total sensible heat generated by pigs, q_H (W) is the heat generated by fuel heaters, q_B (W) is the building envelope heat loss, q_F (W) is the ventilation heat loss, t (day) is time, $\rho_{\bar{a}}$ (kg m^{-3}) is the air density, V (m^3) is the volume of the barn, and C_p (J kg^{-1} °C^{-1}) is the specific heat of the air.

Based on the control volume approach, the humidity production can be described as

$$\rho_{\bar{a}} V \frac{dW_i}{dt} = \dot{m}_a (W_o - W_i) + \dot{W}_1 + \delta\, \dot{W}_m \tag{2.3}$$

where W_i (kg water vaper/ kg dry air) is indoor air humidity ratio, m_a (kg/s) is the ventilation air flow rate, W_o (kg water vaper/ kg dry air) is the outside air humidity ratio, δ is operating cooling facility or not, W_m (kg / s) is the water vapor production from evaporative cooling facilities, W_1 (kg /s) is the swine water vapor production and is a function of latent heat production.

While most of the parameters can be defined directly from the swine barn specifications, the sensible and latent heat production from the pig involves biological activities. Swine growth model developers estimate the heat production based on simulating nutrient and energy partitioning schemes that require a complicated parameter calibration process (Usry et al., 1992; Green and Whittemore, 2003). In order to avoid difficulties in estimating heat production based on the swine growth model, other researchers applied empirical relationships between the heat production and indoor temperature.

Those researchers measured and developed individual livestock heat production models that include levels of animal activity (Albright, 1990; Brown-Brandl et al., 2004; Pedersen & Sallvik, 2002). When the animal activity level is high, the animal inside the barn will generate more heat. By assuming a sinusoidal activity level, researchers estimated the heat production profile within one day. More recently, Brown-Brandl et al. (2014) published results of new experiment for modern swine heat and moisture production on the farm level. The experiment provided more accurate moisture production on the farm level compared to prior estimations that aggregated the individual moisture production. While there exist latent heat production differences between studies, experiment results from Brown-Brandl et al. (2014) showed a similar level of sensible heat production compared to previous research.

In addition to the lumped variable model, researchers have also developed computational fluid dynamic (CFD) models to estimate the spatial variability of the temperature/air flow inside the barn. Zhang et al. (1992) simulated the transient thermal response by taking into account spatial variability for ventilation design. While Zhang et al. (1992)'s CFD results showed the capacity to analyze different control strategies with regard to airflow inside the barn, the model did not consider the effect of pigs inside the barn. In order to consider the effect of pigs inside the barn on the indoor environment simulation, Svidt et al. (1998) simulated air velocity distribution in an occupied swine barn. Svidt et al. (1998) simplified the model based on several assumptions due to limitations of computation power at the time. Zhang et al. (2001) further developed a CFD model that considered constant heat production from individual swine and simulated the swine barn indoor environment. Ecim-Djuric and Topisirovic (2010) applied Zhang et al. (2001)'s model by optimizing the energy efficiency of a swine building and suggested better designs for livestock housing relative to energy efficiency. These CFD models provide detailed indoor environment spatial-temporal information and recommendations for better design of the barn, but the recommendations are limited by boundary condition assignments and complex parameters input. These CFD approaches for swine barn operation also did not consider pig growth and heat production relative to different indoor temperatures. The complex dynamics between CFD environment simulation and heat production from the pig makes it difficult to integrate the swine growth-CFD model.

2.4 Swine Barn Operation Strategies

In order to create a comfortable indoor environment (thermalneutral zone) for swine growth, researchers aim to control the indoor environment to meet the appropriate indoor setpoint condition. The indoor setpoint, which is suggested to be based mostly on the pig live weight, aims to maintain a high growth rate. In addition to the indoor temperature, humidity is another critical factor that affects the comfort level of swine. While researchers aim to control the indoor environment, the indoor setpoint is not always achievable due to the limitations imposed by the outdoor environment and the facilities, including factors such as ventilation and heating capacity. Therefore, the following section focuses on research related to model-based swine barn environmental controls and swine production evaluation.

To prevent heat stress during summer, researchers applied evaporative cooling, for example, evaporative cooling pads and misting/sprinkling systems, to keep the indoor temperature low. Panagakis et al. (1996) used AGRISIM transient simulation of a swine barn to evaluate the misting cooling performance. That simulation is based on a constant pig weight and aims to create a comfortable environment based on the thermal-humidity index. Their simulation results show a positive effect on reducing heat stress with use of a misting system; however, the results were limited to a constant size of swine and did not discuss the entire season effect.

Different control strategies related to the controller are also discussed by researchers. Chao et al. (2000) built a computational model to compare the differences between a conventional ventilation system and a fuzzy logic control system. Their results showed improvements in energy consumption by implementing a fuzzy logic control system relative to fluctuating outdoor temperatures and setpoint step changes.

Lambert et al. (2001) compared different kinds of control systems by swine barn and controller simulation. Their research adopted heat production relationships in CIGR (1984) and assumed a linear growth for the grow-finish stage from 25 kg to 105 kg. Based on simulation results, Lambert et al. (2001) further developed and evaluated a humidity controller and benefits of temperature-humidity control systems over temperature control systems under cold weather conditions. Their results were interesting with regard to the entire season effect but did not consider varying pig growth rates based on different ages, the environment, and diet.

Morsing et al. (2005) also simulated indoor psychrometric properties, air quality, and energy consumption based on levels of animal heat and moisture production on swine barns as suggested by CIGR (2002) in Portugal, Finland, and Denmark. The set-point that was selected linearly decreased based on bedding material. The research also considered the indoor humidity setpoint based on a constant summation for indoor temperature and humidity. The entire season results provided a more comprehensive comparison of different control strategies, but the linear growth assumption neglected to take into account the relationships between pig growth and the indoor environment.

Bridges et al. (1998) connected the NC-204 swine growth model (NCPIG) and naturally-ventilated swine barn simulations to evaluate economic returns of misting-cooling systems for the entire season. Their results suggested that a misting cooling system is beneficial for swine growers to realize better economic returns. The same research group compared the NCPIG model with results of an on-farm experiment and found the predictions were accurate (Turner et al., 1998). The swine growth - swine barn thermal model demonstrates a system approach to discuss different control strategies; however, the system set up is for natural ventilation and requires extensive model input for the NCPIG model.

While numerous studies discuss swine barn indoor environment control as a way to achieve the indoor setpoint, few have considered pig growth performance over an entire growing cycle and the dynamic relationships between swine growth and swine barn thermal characteristics. A comprehensive scheme for understanding the entire growing cycle environmental control strategy evaluation requires an understanding of the dynamic relationships between swine barn thermal characteristics and swine growth process.

2.5 Summary of the Literature Review

1. In the cooling season, experiments showed a leaner body composition, lower feed intake, and slower daily gain. While the diurnal indoor temperature change had no significant effect on pig growth under the *ad-libitum* condition, the average indoor temperature was shown to be influential on pig growth. Experiment results from the literature demonstrate **no** consensus on seasonality effect on the feed conversion ratio (FCR). A more in-depth understanding of the FCR is needed for future discussion. These experimental results will be applied to daily critical indoor temperature assumptions for voluntary dietary intake.

2. Most of the pig growth models evolved to consider comprehensive nutrient partitioning and energy utilization mechanisms, but the complexity of the models impeded the application for use in commercial swine barns. Most of the advanced models require extensive parameter calibration processes and may not be applied to other conditions. Other than simplifying state of the art models, the current research aims to extend the classic nutrient partitioning scheme created by Moughan et al. (1987) by updating the empirical equations and maintaining flexibility of the model parameter.

3. Most comprehensive swine growth models take indoor humidity as an input variable to estimate heat loss from the swine in order to calculate the feed intake amount. These models require complex model schemes that include, for example, core body temperature estimation, to estimate feed intake. Previous studies observed no statistically significant differences between different humidity levels and swine growth performance under the thermalneutral condition although the humidity level under heat stress conditions would have a direct effect on swine physiological response. Yet, the empirical relationships among indoor humidity levels, heat production, and feed intake, have not been well developed. Additionally, the whole barn swine latent heat (moisture) production model based on swine weight and the mass balance method is

not accurate without considering facility moisture production according to recent research. Moreover, there exists an information gap for indoor humidity estimation between swine humidity production and swine production performance. Therefore, the current research estimates swine performance based only on indoor temperature.

4. The computational fluid dynamic (CFD) approach provides excellent spatial information for potential optimum design, but it is also limited by the complex parameter inputs, assumptions on the boundary condition, and computation time. The complexity of the CFD model is an obstacle to combining the heat production model and CFD for the entire growing cycle. The lumped variable models do not provide the spatial information but instead avoid these difficulties. Studies that have focused on the entire growing cycle swine barn operation have also applied the lump variables approach to simulate the indoor environment.

CHAPTER 3: MODIFIED SIMPLE PIG GROWTH MODEL FOR MODERN SWINE: DEVELOPMENT, CALIBRATION, AND VALIDATION

3.1 Introduction

To understand swine growth performance from a quantitative approach, system modeling that incorporates multiple biophysical and empirical relationships has been applied to describe and predict pig growth under different conditions. The relationships among indoor air temperature, nutrients, and efficiency of live weight gain have been quantified by several studies. Moughan, Smith, and Pearson (1987) developed a simple pig growth model for the grow-finish period of swine production to describe pig live weight changes on a daily basis. Unlike Black, Fleming, and Davies (1987) who applied empirical relationships between parameters to determine nitrogen retention, Moughan et al. (1987) constrained body protein retention by requiring a minimum level of body lipid. The Moughan model showed accurate predictions with few parameters but did not take into account environmental factors. Black et al. (1987) developed a model (AUSPIG) that simulates the entire production cycle and includes predictions of the *ad libitum* effect by considering nutrition, genetics, and environment. Researchers (Bridges, Turner, Stahly, Usry, & Loewer, 1992; Bridges, Turner, Usry, & Nienaber, 1992; Usry, Turner, Bridges, & Nienaber, 1992) in the U.S. developed a model (NCPIG) based on the interaction of environmental factors, feed intake, and genotypes. That model also predicted how *ad libitum* intake influences pig growth. However, the full NCPIG model is difficult to use due to its complicated parameters. Researchers in Europe developed a model (IMS PIG) based on a novel nutrient scheme and modeling architecture that provide for variable nutrient absorption efficiency; however, the model scheme requires serially slaughtered swine to better calibrate the model (Green and Whittemore, 2005; Green and Whittemore, 2003).

There are only a few research documents that focus on more recent swine growth model parameters. Specific parameters, such as maximum protein deposition rate, minimum protein to lipid ratio, and energy requirements to deposit protein and lipid, have not been updated for more than 15 years. Because modern swine grow leaner and faster and consumes more feed, it is necessary to calibrate these parameters and validate the model with more recent pig growth data. Moreover, in order to simulate swine growth without overcomplicated parameter calibration, it is important to calibrate a model that is comprehensive but with minimum amounts of parameters.

The overall goal of this chapter is to develop an existing model with limited parameters that can simulate more recent swine growth performance under different temperatures. The specific objectives are 1) to develop a modified simple pig growth model (MSPGM) based on more recent research. 2) to calibrate the model and identify the differences between benchmark parameters from previous research and calibrated parameters from the recent experiment, and 3) to validate the proposed model and understand the limitations of the model prediction under different conditions.

3.2 Materials and Methods

3.2.1 Model development

The current study follows the simple pig growth model (SPGM) scheme developed by previous research (De Lange, 1995; Moughan et al., 1987) that was selected for its simplicity. As appropriate, modifications were included based on several new empirical relationships and parameters. Whereas De Lange's model assumes that pig growth occurs in thermoneutral zones, this simulation considered indoor temperature as an environmental factor that affects pig growth.

Basic principles of energy and amino acid partitioning for the period of swine growth are included in the MSPGM. The following assumptions are also included in the MSPGM: 1) Genetic differences between pigs are presented by parameters: e.g., maximum daily protein deposition, minimum body lipid to protein ratio. 2) Dietary nutrients other than amino acids and energy (such as vitamins, minerals, and essential fatty acids) are not limiting to growth. 3) MSPGM presents an only average performance with no individual variation included in the model. Disease effect is not considered in this study.

This study programs the MSPGM as an S-function in Simulink (Version 8.2; Mathworks Inc., 2013) and aims to apply it for swine barn operations. Based on the general scheme of nutrient partitioning, the model proposed by this study aims to estimate final body weight on a daily basis. Due to the limitation on length, this paper mentions only the modified empirical equations based on recent documents. More model details are listed in Appendix A.

Instead of assuming a minimum lipid/protein ratio for initial pig, this study adopts empirical equations from NRC (2012) to estimate the initial lipid/protein ratio (InitialLP).

$$InitialLP = (\ 0.305 - 0.00875 \times Pd_{max}) \times W_0^{0.45} \tag{3.1}$$

where Pd_{max} is the maximum protein deposition rate, and W_0 is the initial mean pig live weight.

The reference voluntary daily metabolizable energy intake ($MEvi$, kJ d^{-1}) is given as a function of body weight (W, kg) as modified by Schinckel et al. (2012) equations. This paper introduces a modification factor (M_{FI}) to Schinckel et al. (2012) equations in order to increase the flexibility as follows:

$$MEvi = M_{FI} \times a(1 - e^{-e^{b} \times W^{c}}) \tag{3.2}$$

where W is the pig live weight, a and b are constants that affect ME intake. Constants a, b, and c are different across general swine, gilts, and barrows as shown in Table 3.1.

Table 3.1 Constants for metabolizable energy intake estimation

Type of Swine	***a***	***b***	***c***
Gilts	46400.56	-3.666	0.9089
Barrows	46024.00	-5.077	1.320

To represent the impact of environmental temperature on ME intake, the lower critical temperature (*LCT*) is estimated and *MEvi* is adjusted.

$$LCT = 17.9 - 0.0375 \times W \tag{3.3}$$

$$Fraction\ of\ MEvi\ intake = 1 - 0.012914 \times \left[T_i^C - (LCT + 3)\right]$$
$$-0.001179 \times \left[T_i^C - (LCT + 3)\right]^2$$

where the T_i^C is the daily critical indoor temperature in °C.

While the SPGM uses a fixed maximum protein deposition rate (Pd_{max}), this study assumes different Pd_{max} with different pig live weight based on linear interpolations from referenced Pd_{max} (Pd_{max}^R) published in NRC (2012) and shown in blue solid line in Figure 3.1. However, because different swine genotypes might have different Pd_{max} curve, this study assumes a Pd_{max} as

$$P_{dmax} = rPd_{max} \times Pd_{max}^R \tag{3.4}$$

where rP_{dmax} is the Ratio to reference maximum daily protein deposition rate. The modified Pd_{max} curve with rPd_{max} = 1.1 and rPd_{max} = 0.9 is also shown in Figure 3.1.

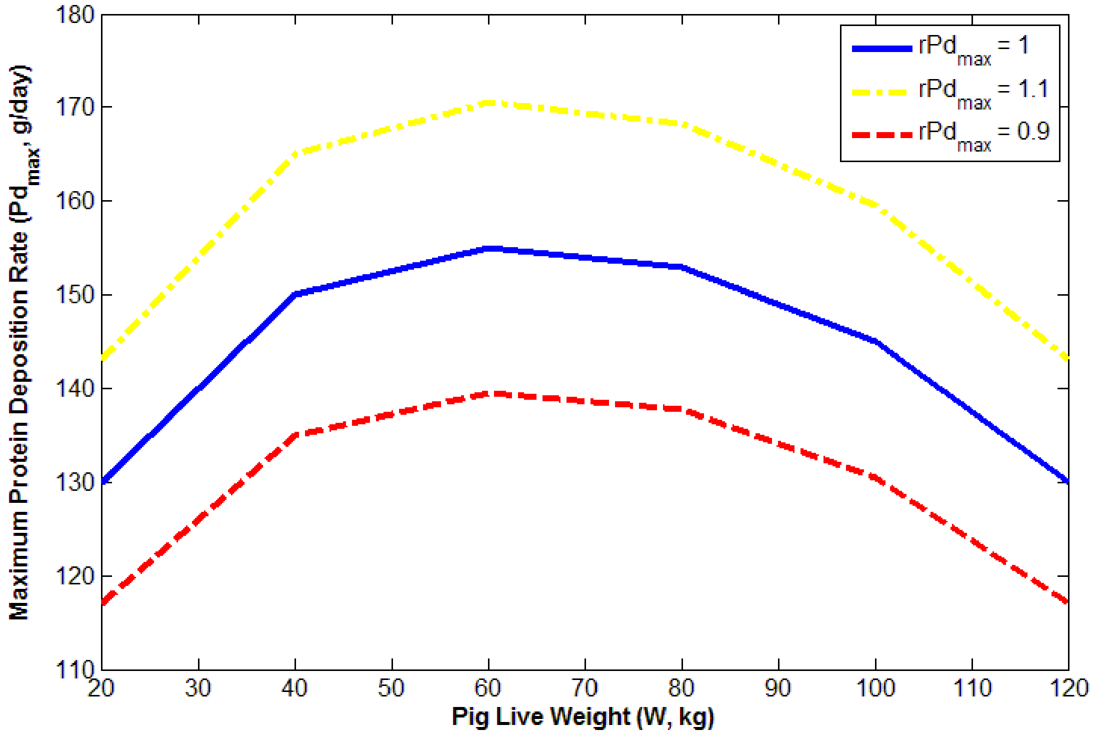


Figure 3.1 Referenced maximum protein deposition rate (Pd_{max}) curve refers to different pig live weight and different rPd_{max}. The blue solid line is the Pd_{max} curve adopted from NRC(2012), where rPd_{max} equals to 1. The yellow dotted line is the Pd_{max} curve with rPd_{max} equals to 1.1 and the red dash line is the Pd_{max} curve with rPd_{max} equals to 0.9. These Pd_{max} curves demonstrates potential genotypes variations.

De Lange et al. (1995) and Moughan et al. (1987) assume the "good" pig has a minimum body lipid to protein ratio ($minLP$) that equals 1 and "poor" pig has a higher $minLP$ at 1.4. Although modern swine are shown to be leaner, the $minLP$ has not been updated for modeling purpose. The current research keeps $minLP$ at 1 as a benchmark, but aims to calibrate it to fit swine performance in experiments. Two fundamental numbers - energy requirements to lipid deposit (Eld) and energy requirements to protein deposit (Epd) - have been updated from ARC (1981) to Tess et al. (1984) and NRC (1998). Because there are no recent publications on both parameters, the current research takes Tess et al. (1984) and NRC (1998) as benchmarks and generalizes the number as shown in Equation (3.5)

$$Epd = rEpd \times 44.35\ kJ\ g^{-1} \tag{3.5}$$

$$Eld = rEld \times 52.3\ kJ\ g^{-1}$$

While SPGM estimate maintenance energy (Em) requirements are based only on live weight, this study considers the thermogenesis based on environment temperature. In cold weather conditions, *Em* will be higher due to the needs of thermogenesis (NRC, 2012). If the temperature is higher than LCT, there is no thermogenesis. If the temperature is lower than LCT, the relationship in Eq. (3.8) takes place:

$$Em = standard\ Em + Em\ for\ thermogenesis \tag{3.6}$$

$$Standard\ Em = 824.248 \times W^{0.60} \tag{3.7}$$

$$Em\ for\ thermogenesis = 0.07425 \times \left(LCT - T_i^C\right) \times Standard\ Em \tag{3.8}$$

3.2.2 Model calibration and validation

In MSPGM model scheme, feed intake (FI), maximum protein deposition rate (Pd_{max}), and minimum body lipid to body protein ratio ($minLP$), are affected by genotype. Among these three parameters, only *FI* was documented in 2012 by Schinckel et al. based on different pig weight for more recent swine production. On the other hand, $Pd_{max}$and $minLP$ have not been updated with new experiments. Because *FI* was published more recently, the current research calibrates the *FI* with a smaller searching range. The current study aims to *calibrate* and *validate* the model based on training three genotype-related parameters with the same type of swine in two separate growing cycles.

3.2.2.1 Experiment Description

In order to calibrate and validate the MSPGM swine production model, two experiments were carried out at the Swine Research Center (SRC) of the University of Illinois, Urbana-Champaign, in a typical controlled university research facility. More discussion on swine growth conditions and diet can be found in Estrada (2017). For calibration and validation purposes, the current research calibrates the MSPGM swine production model based only on growing-finishing trial swine from 30 kg to 127 kg, which has a consistent pen size (4 pig per pen) and growth performance across the growing cycle. All the swine are grown under a mixed-sex pen condition with three diet treatments as shown in Table 3.2 a) to 3.2 c). Individual swine weight and the feed intake for each pen were measured every two weeks. Individual swine backfat probe thickness was measured three times during the experiment. Both experiments have two temperature sensors located near pen #34 and pen #22 to record temperature every 10 minutes to present average spatial temperature. The daily average temperature for the individual experiment was further estimated to match the MSPGM model prediction temporal resolution. The experiment site diagram is shown in Figure 3.2. Experiment 1 was conducted in the Grower 1 North Room from September 9, 2017 to December 12, 2017, with 24 pigs. Experiment 2 was conducted in Grower 1 South Room from September 23, 2017, to December 21, 2017, with 36 pigs. Observations from Experiment 1 were taken as the training dataset to calibrate the model parameters based on indicators such as live weight, feed intake, and backfat probe thickness to better evaluate more recent swine growth performance. Based on the calibrated model parameters, observations from Experiment 2 were taken to validate the model performance. Both Experiments raised swine with the same breeding line, but the indoor temperature was different as shown in Figure 3.3.

Table 3.2 a) Diet formulation and calculated and analyzed composition for Early Growing phase (BW = 29 to 64 kg)

	Diet					
	Control		CGM 20% - No Fat		CGM 20% + Fat	
Ingredient, %						
Corn	72.04		60.7		55.33	
Corn germ meal[1]	-		20		20	
Soybean meal[1]	24.57		15.81		17.99	
Fat (Yellow grease)	0.5		0.5		3.77	
Limestone	1.03		1.22		1.2	
Mono-cal 21% P	0.73		0.49		0.49	
Salt	0.5		0.49		0.46	
L-Lysine HCl- Dry (98.5%)	0.31		0.4		0.4	
Methionine (HMB[2])	0.12		0.11		0.13	
Threonine (98%)	0.06		0.08		0.08	
Trace minerals premix	0.08		0.08		0.08	
Copper chloride (58%)	0.03		0.03		0.03	
Vitamins premix	0.03		0.03		0.03	
Phytase(Ronozyme HiPhos 2500 GT)	0.01		0.02		0.02	
Red iron oxide	-		0.04		-	
Composition	Calculated	Analyzed[3]	Calculated	Analyzed[3]	Calculated	Analyzed[3]
ME, kcal/kg	3296	-	3138	-	3297	-
Dry matter, %	86.52	86.62	86.73	87.01	87.17	87.54
Crude Protein, %	16.8	17.4	16.5	16.7	17.16	17.7
Crude Fat, %	2.71	2.92	2.65	3.53	5.57	6.81
Crude Fiber, %	1.51	2.5	2.64	3.88	2.64	3.66
NDF, %	6.17	8	12.21	14.4	12.02	12.7
ADF, %	2.84	3.3	4.49	4.4	4.52	5
Calcium, %	0.63	0.65	0.63	0.72	0.63	0.67
Phosphorus, %	0.52	0.53	0.52	0.57	0.52	0.56
Digestible phosphorus, %	0.33	-	0.31	-	0.31	-
Calcium:Phosphorus	1.2	-	1.2	-	1.19	-
Sodium, %		0.2	0.22	0.21	0.2	0.2
Lysine, %	1.11	1.14	1.09	1.14	1.14	0.19
SID[4] lysine, %	1	-	0.95	-	0.99	-
SID[4] lysine:ME, g:Mcal	3.02	-	3.01	-	3.01	-
SID[4] AA:SID[4] Lys ratio						
Met + Cys	0.57	-	0.57	-	0.57	-
Tryptophan	0.18	-	0.17	-	0.17	-
Threonine	0.59	-	0.6	-	0.6	-
Isoleucine	0.6	-	0.56	-	0.56	-
Valine	0.65	-	0.67	-	0.66	-

[1]Ingredient source: Archer Daniels Midland (Dectur, IL)
[2]HMB = 2-hydroxy-4-(methylthio) butanoic acid
[3]Diet analyses: proximates were conducted by Midwest Labs using wet chemestry; and aminoacids were conducted by Ajinomoto Heartland, Inc. laboratory using High-Performance Liquid Chromatography (HPLC).
[4]SID = standardized ileal digestible

Note. Adapted from "Table 4.2." by Estrada, 2017. *Effects of body weight and research conditions on the productive energy content of corn germ meal fed to growing-finishing pigs* (Doctoral dissertation, University of Illinois at Urbana-Champaign).

Table 3.2 b) Diet formulation and calculated and analyzed composition for Late Growing phase (BW = 64 to 96 kg)

	Diet					
	Control		CGM 20% - No Fat		CGM 20% + Fat	
Ingredient, %						
Corn	80.98		68.01		63.18	
Corn germ meal[1]	-		20		20	
Soybean meal[1]	16.35		9.34		10.98	
Fat (Yellow grease)	0.35		0.35		3.62	
Limestone	0.94		1.13		1.11	
Mono-cal 21% P	0.41		0.11		0.12	
Salt	0.5		0.5		0.46	
L-Lysine HCl-Dry (98.5%)	0.24		0.3		0.29	
Methionine (HMB[2])	0.04		0.02		0.04	
Threonine (98%)	0.05		0.04		0.05	
Trace minerals premix	0.08		0.08		0.08	
Copper chloride (58%)	0.03		0.03		0.03	
Vitamins premix	0.03		0.03		0.03	
Phytase(Ronozyme HiPhos 2500 GT)	0.02		0.03		0.03	
Red iron oxide	-		0.04		-	
Composition	Calculated	Analyzed[2]	Calculated	Analyzed[2]	Calculated	Analyzed[2]
ME, kcal/kg	3311	-	3152	-	3311	-
Dry matter, %	86.31	86.51	86.54	86.96	86.98	87.57
Crude Protein, %	13.46	14.8	13.81	15.1	14.25	15.8
Crude Fat, %	2.78	3.25	2.68	3.24	5.61	5.57
Crude Fiber, %	1.39	1.04	2.55	2.95	2.54	3.4
NDF, %	6.15	8.2	12.21	14.5	12.02	14.8
ADF, %	2.53	4.3	4.25	6.1	4.25	7.1
Calcium, %	0.5	0.48	0.5	0.59	0.5	0.59
Phosphorus, %	0.42	0.45	0.42	0.51	0.42	0.52
Digestible phosphorus, %	0.26	-	0.25	-	0.25	-
Calcium:Phosphorus	1.19	-	1.2	-	1.2	-
Sodium, %	0.22	0.2	0.22	0.21	0.2	0.22
Lysine, %	0.84	0.87	0.83	0.9	0.87	0.95
SID[4] lysine, %	0.74	-	0.71	-	0.74	-
SID[4] lysine:ME, g:Mcal	2.24	-	2.24	-	2.24	-
SID[4] AA:SID[4] Lys ratio						
Met + Cys	0.57	-	0.57	-	0.57	-
Tryptophan	0.18	-	0.18	-	0.18	-
Threonine	0.62	-	0.62	-	0.62	-
Isoleucine	0.62	-	0.59	-	0.6	-
Valine	0.7	-	0.75	-	0.74	-

[1]Ingredient source: Archer Daniels Midland (Decatur, IL)
[2]Diet analyses: proximates were conducted by Midwest Labs using wet chemestry; and aminoacids were conducted by Ajinomoto Heartland, Inc. laboratory using High-Performance Liquid Chromatography (HPLC).
[3]HMB = 2-hydroxy-4-(methylthio) butanoic acid
[4]SID = standardized ileal digestible

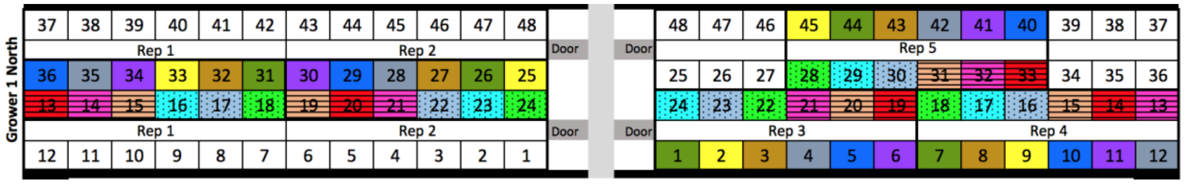
Note. Adapted from “Table 4.3.” by Estrada, 2017. *Effects of body weight and research conditions on the productive energy content of corn germ meal fed to growing-finishing pigs* (Doctoral dissertation, University of Illinois at Urbana-Champaign).

Table 3.2 c) Diet formulation and calculated and analyzed composition for Finishing phase (BW = 96 to 127 kg).

	Diet					
	Control		CGM 20% - No Fat		CGM 20% + Fat	
Ingredient, %						
Corn	84.39		70.02		65.35	
Corn germ meal[1]	-		20		20	
Soybean meal[1]	13.2		7.6		9.08	
Fat (Yellow grease)	0.35		0.35		3.66	
Limestone	0.91		1.1		1.05	
Mono-cal 21% P	0.25		-		-	
Salt	0.46		0.46		0.41	
L-Lysine HCl-Dry (98.5%)	0.21		0.23		0.23	
Threonine (98%)	0.04		0.02		0.02	
Trace minerals premix	0.06		0.06		0.06	
Copper chloride (58%)	0.03		0.03		0.03	
Vitamins premix	0.03		0.03		0.03	
Phytase (Ronozyme HiPhos 2500 GT)	0.03		0.04		0.04	
Mycotoxin binder (Engage-M)	0.05		0.05		0.05	
Red iron oxide	-		0.04		-	
Composition	Calculated	Analyzed[2]	Calculated	Analyzed[2]	Calculated	Analyzed[2]
ME, kcal/kg	3320	-	3158	-	3320	-
Dry matter, %	86.24	86.12	86.48	86.38	86.92	86.31
Crude Protein, %	12.17	13.1	13.03	13.8	13.41	14.2
Crude Fat, %	2.85	3.41	2.72	3.61	5.69	5.55
Crude Fiber, %	1.34	0.82	2.52	2.05	2.51	1.82
NDF, %	6.14	8.2	12.21	13.8	12.02	14.4
ADF, %	2.41	4.3	4.18	5.3	4.18	5.7
Calcium, %	0.45	0.5	0.46	0.54	0.45	0.47
Phosphorus, %	0.38	0.4	0.39	0.41	0.39	0.41
Digestible phosphorus, %	0.24	-	0.23	-	0.23	-
Calcium:Phosphorus	1.2	-	1.2	-	1.17	-
Sodium, %	0.2	0.17	0.2	0.18	0.18	0.17
Lysine, %	0.73	0.8	0.73	0.78	0.76	0.83
SID[3] lysine, %	0.64	-	0.61	-	0.64	-
SID[3] lysine:ME, g:Mcal	1.93	-	1.93	-	1.93	-
SID[3] AA:SID[4] Lys ratio						
Met + Cys	0.57	-	0.61	-	0.59	-
Tryptophan	0.18	-	0.19	-	0.19	-
Threonine	0.64	-	0.64	-	0.64	-
Isoleucine	0.64	-	0.64	-	0.64	-
Valine	0.74	-	0.83	-	0.81	-

[1]Ingredient source: Archer Daniels Midland (Decatur, IL).
[2]Diet analyses: proximates were conducted by Midwest Labs using wet chemestry; and aminoacids were conducted by Ajinomoto Heartland, Inc. laboratory using High-Performance Liquid Chromatography (HPLC).
[3]SID = standardized ileal digestible

Note. Adapted from "Table 4.4." by Estrada, 2017. *Effects of body weight and research conditions on the productive energy content of corn germ meal fed to growing-finishing pigs* (Doctoral dissertation, University of Illinois at Urbana-Champaign).



201617	#	Study Period	Diet
	1	Growing-Finishing	0% CGM - Control **(1)**
	2	Growing-Finishing	20% CGM - No Added Fat **(2)**
	3	Growing-Finishing	20% CGM + Added Fat **(3)**
	4	Early Growing	0% CGM - Control **(1)**
	5	Early Growing	20% CGM - No Added Fat **(2)**
	6	Early Growing	20% CGM + Added Fat **(3)**
	7	Late Growing	0% CGM - Control **(1)**
	8	Late Growing	20% CGM - No Added Fat **(2)**
	9	Late Growing	20% CGM + Added Fat **(3)**
	10	Finishing	0% CGM - Control **(1)**
	11	Finishing	20% CGM - No Added Fat **(2)**
	12	Finishing	20% CGM + Added Fat **(3)**

Study Period	Body Weight, kg
Growing-Finishing	30 - 127
Early Growing	30 - 64
Late Growing	64 - 95
Finishing	95 - 127

Figure 3.2 Site diagram of the SRC Grower 1 North and Grower 1 South. Only Growing-Finishing trials were used for the calibration and validation process (color code 1-3)

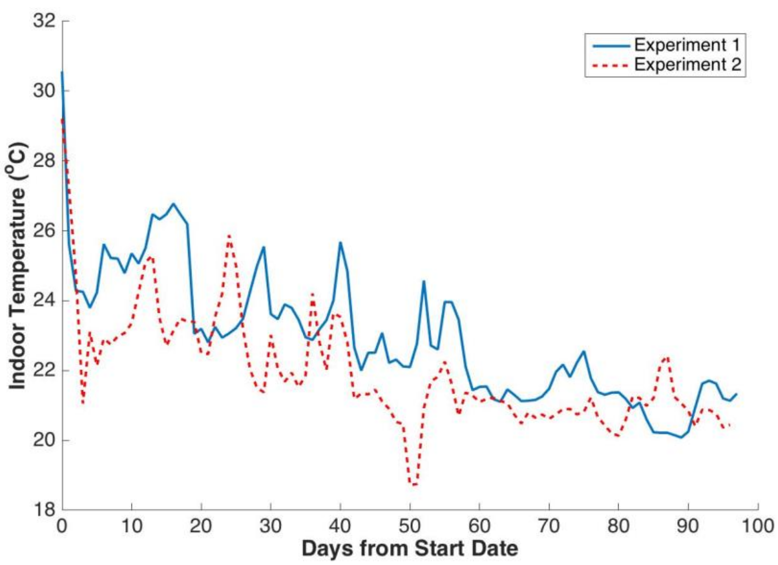


Figure 3.3 Temperature profile for Experiment 1 and Experiment 2.

3.2.2.2 Calibration process

The current research calibrates the model based on observations from Experiment 1 observations. The calibration model applied observations such as pig weight, cumulative feed intake, and backfat probe thickness, to train the model parameters to evaluate the swine growth performance. In order to calibrate the model, the current research aimed to minimize the error rate of pig weight, cumulative feed intake, and backfat probe thickness as shown in Equation (3.9):

$$\min \sum_{D=1}^{D=m} \sum_{D=1}^{D=n} \left(\frac{\widehat{W}_i^D - W_i^D}{W_i^t} \right)^2 + \sum_{t=1}^{t=m} \sum_{i=1}^{i=n} \left(\frac{\widehat{CFI}_i^D - CFI_i^D}{CFI_i^t} \right)^2 + \sum_{D=1}^{D=k} \sum_{D=1}^{D=n} \left(\frac{\widehat{BF}_i^D - BF_i^D}{BF_i^D} \right)^2 \tag{3.9}$$

$$s.t. \quad (\widehat{\boldsymbol{W}}_{\boldsymbol{\iota}}, \widehat{\boldsymbol{CFI}}_{\boldsymbol{i}}, \widehat{\boldsymbol{BF}}_{\boldsymbol{\iota}}) = \boldsymbol{f_Y}(W_i^0, rPd_{ma□}, minLP, MFI)$$

$$1 \le rPd_{max} \le 1.4$$

$$0.9 \le MFI \le 1.2$$

$$0.9 \le minLP \le 1.4$$

$$0.9 \le Eld \le 1.1$$

$$0.9 \le Epd \le 1.1$$

where

$\boldsymbol{f_{MSPGM}}$ is the modified simple pig growth model (MSPGM). Noted that the model applied true observed daily average temperature to perform calibration.

$\widehat{\boldsymbol{W}}_{\boldsymbol{\iota}}$ denotes simulated weight time series vector for *i*th pig

$\widehat{W}_i^t$ denotes simulated weight for *i*th pig at time *t*, and is an element of $\widehat{\boldsymbol{W}}_{\boldsymbol{\iota}}$

W_i^t denotes observed weight for *i*th pig at time *t*

W_i^0 denotes initial weight for *i*th pig

$\widehat{\boldsymbol{CFI}}_{\boldsymbol{i}}$ denotes simulated cumulative feed intake time series vector for *i*th pig

$\widehat{CFI}_i^t$ denotes simulated cumulative feed intake for *i*th pig at time *t*, and is an element of $\widehat{\boldsymbol{CFI}}_{\boldsymbol{i}}$

CFI_i^tdenotes observed cumulative feed intake for *i*th pig at time *t*

$\widehat{\boldsymbol{BF}}_{\boldsymbol{\iota}}$ denotes simulated backfat probe thickness time series vector for ith pig

$\widehat{BF}_i^t$denotes simulated backfat probe thickness for *i*th pig at time *t*, and is an element of $\widehat{\boldsymbol{BF}}_{\boldsymbol{\iota}}$

BF_i^tdenotes observed backfat probe thickness for *i*th pig at time *t*

m denotes the total number of observation for live weight

n denotes the total number of pigs

k denotes the total number of observation for backfat probe thickness

rPd_{max} denotes the ratio compare the referenced Pd_{max} (Balck et al.,1988)

MFI denotes the ratio compared to the referenced feed intake (Schinckel et al., 2012)

$minLP$ denotes to minimum lipid to protein ratio. 1 for "good" pig and 1.4 for "bad" pig (De Lange et el., 1995)

The optimization process was performed in Matlab 2017 based on the simplex method from Lagarias et al. (1998). The optimization method does not guarantee to converge to a global minimum, therefore, constraints of each parameter were introduced to assure the solution was in our interest. Each optimum parameter searching started with a random sampled number in solution space. Assuming the genotype had increased on Pd_{max}dramatically, the optimization process assigned a larger range as a constraint. Because feed intake information has been published more recently, a smaller range of the optimization process was introduced. Assuming modern swine growth had better performance than "good" pig, as defined by De Lange et al. (1995), the process setup was 0.9 to 1.4 for the $minLP$ range, where 1.4 is defined as "bad" performance pig in De Lange et al. (1995).

To ensure the minimum solution within the solution space, the current research random sampled 100 points within the solution space as initial solutions for the Lagarias et al. approach to evaluate the consistency of the optimization approach.

In order to evaluate the calibrated model performance, several evaluation methods are discussed, as follows. A calibration curve analysis was first applied and discussed to provide an overview of the predicted results based on regression analysis. In the calibration curve analysis, the simulated result is defined as the independent variable and the observation is defined to be dependent variable in the regression. A perfect model result will lie on the 45degree line, where the slope is equal to one. By forcing interception equals to zero, the slope of the regression result indicates the goodness of the prediction result. The t-test is performed to identify if the slope is significantly different from one. If the slope is significantly different from one, the model prediction accuracy is not statistically significant. Although the calibration curve approach identifies a general tendency for prediction accuracy, it does not consider the absolute error for the prediction result.

To better present the prediction accuracy, this paper presents the root mean square error (RMSE) of the error rate for individual observations. The RMSE of the error rate direct indicates the performance of the simulation result. RMSE result will be further discussed and evaluated for future model usage.

3.2.2.3 Validation process

To better understand the calibrated model performance, a validation process was conducted to evaluate prediction results. Observations from Experiment 2, which had similar genomic performance compared to Experiment 1 but with different indoor temperature conditions, were applied to compare with the calibrated model simulation result. The calibration curve approach and RMSE evaluation were also applied to present the model performance on the validation dataset. A further discussion on the model performance will be presented in the 3.3.2 Section in Chapter 3.

3.3 Results and Discussion

3.3.1 Calibration results

Based on the optimizing ratio to the referenced maximum protein deposition ratio (rPd_{max}), the minimum lipid to protein ratio ($minLP$), and the Modified Feed Intake coefficient

(MFI), the current research minimized the error function as introduced in the Methodology section. Figure 3.4 demonstrates the histogram of both initial 100 random sampled initial solutions and optimized solutions for the Lagarias et al. approach.

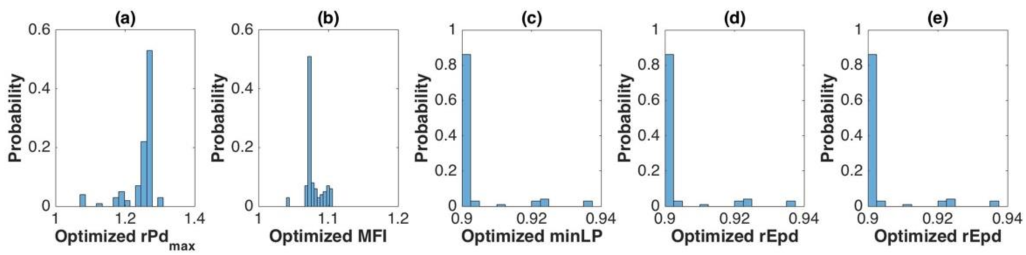


Figure 3.4 The optimized solution histogram from random sampled initial solution in solution space for (a) ratio to referenced maximum protein deposition rate (rPd_{max}), (b) modified feed intake (*MFI*), (c) minimum body lipid to protein ratio (*minLP*), (d) ratio to referenced energy requirements for protein deposition (*rEpd*), and (e) ratio to referenced energy requirements for protein deposition (*rEld*)

The optimum trained parameters are shown as in Table 3.3:

Table 3.3 Optimum coefficient for calibration results

Coefficient	rPd_{max}	MFI	$minLP$	$rEpd$	$rEld$
Optimum Result	1.27	1.07	0.90	0.90	0.91
Referenced number	1	1	1	1	1

The optimum coefficient for the calibration process indicates a 27% increase in the maximum protein deposition rate compared to Black et al. (1987). Feed intake is 7% more than Schinckel et al. (2012). The $minLP$ is 10% less than “good pig” defined by De Lange et al. (1995). The $rEPd$ is 10% more efficient than Tess et al. (1984), and $rEld$ is 9% more efficient than NRC (1998).

The statistics for the regression result are listed in Table 3.4. Only the slope of pig live weight is not statistically significantly different from 1 as shown in Figure 3.5. Both feed intake and backfat probe thickness have smaller slopes, which indicate underestimation compared to the true observation as shown in Figure 3.6 and Figure 3.7. Pig live weight simulation has the best accuracy and precision based on the slope and the standard error. Backfat probe thickness has the smallest slope and largest standard error for the slope estimation, indicating both poor precision and accuracy. Feed intake performs moderate accuracy, but a lower precision compared to pig live weight based on the standard error. Although the feed intake slope is statistically different than 1 ($\alpha = 0.05$), the p-value is close to 5%.

In regression, the root mean square error (RMSE) is another general evaluation method of the model performance. The RMSE for the pig live weight is 1.75 kg for all the simulated pig live weight and observed pig live weight. Feed Intake per pig has a higher RMSE at 9.30 kg. Backfat probe thickness shows a 1.75mm RMSE.

Table 3.4 Calibration results for regression and RMSE

Indicators	Slope	Standard Error	P value for Slope ≠1	RMSE
Weight	0.9985	0.0031	0.6256	1.75 kg
Feed Intake	0.9789	0.0103	0.0467	9.30 kg
Backfat Probe Thickness	0.9472	0.0142	<0.0001	1.75mm

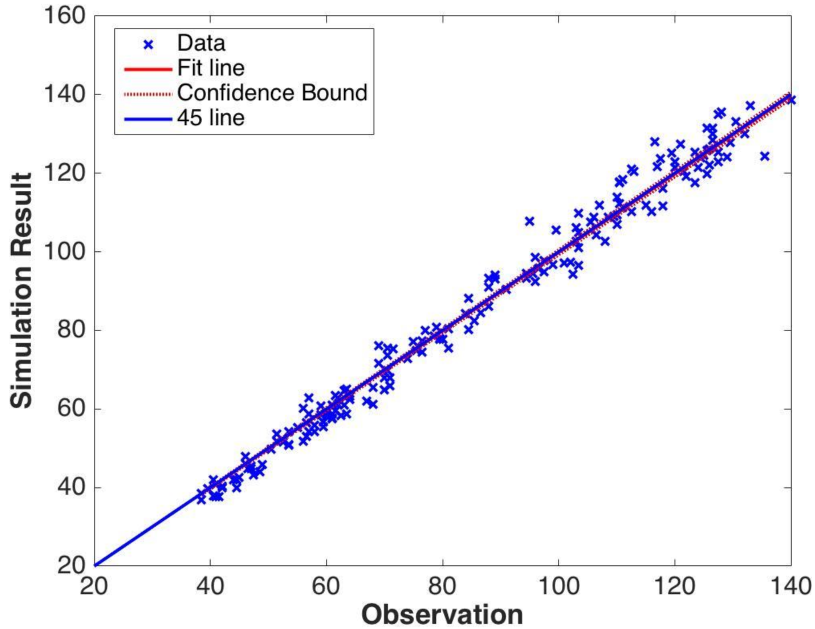


Figure 3.5 The calibration regression of the simulation and observation for pig live weight (kg)

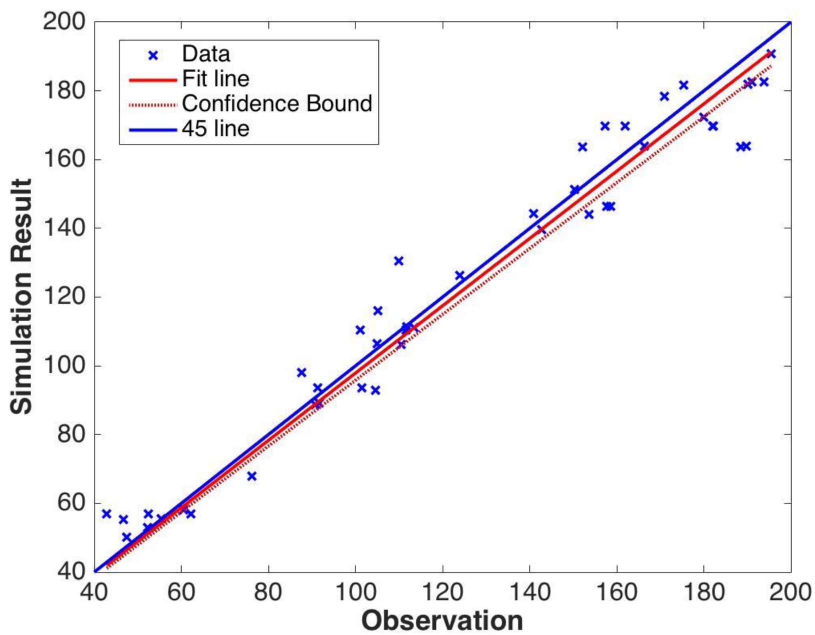


Figure 3.6 The calibration regression of the simulation and observation for recorded feed intake (kg).

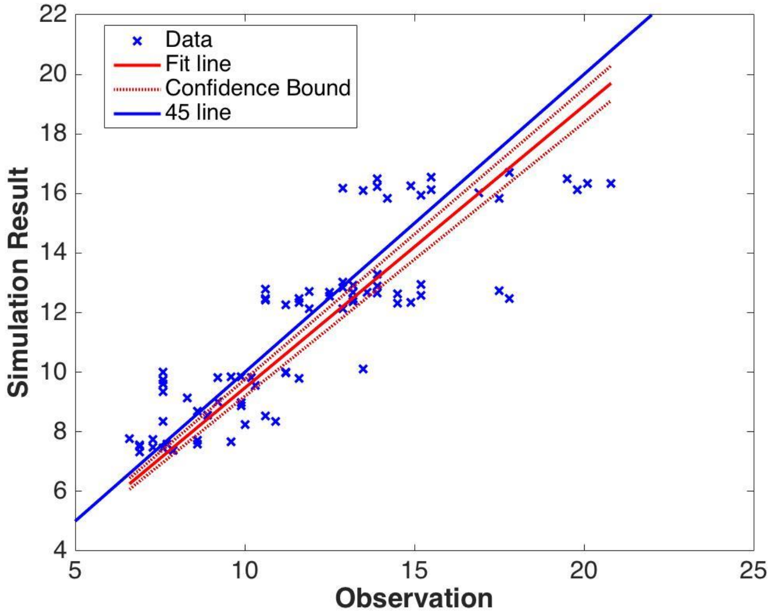


Figure 3.7 The calibration regression of the simulation and observation for backfat probe thickness (mm).

Other than the weight, feed intake, and backfat probe thickness with the time series observation, entire cycle performance such as the average daily gain (ADG) and the feed conversion ratio (FCR) could not be examined by the calibration regression due to the limitation of data amount at entire cycle level. Error histograms were visualized to identify the simulation tendency as shown in Figure 3.8. The errors are estimated by simulation result minus the observation. ADG simulation has a balanced error structure in Figure 3.8.a, the FCR error structure is not normal distributed (Figure 3.8.b)

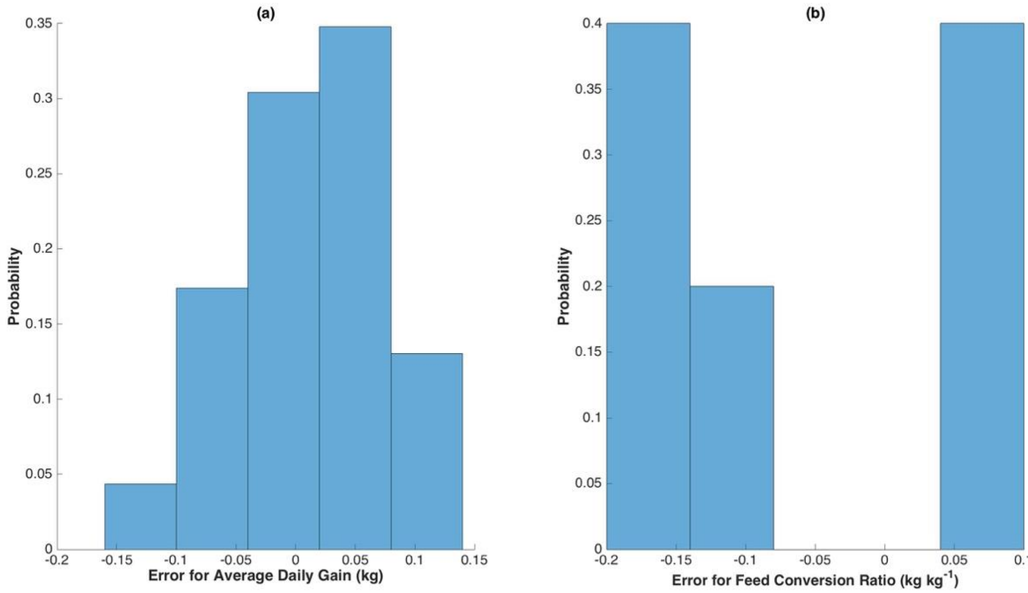


Figure 3.8 The histogram for error in calibration (simulation - observation) for (a) average daily gain and (b) feed conversion ratio

Although RMSE provides a general model performance evaluation for an all growing cycle, it does not consider the model performance related to different pig stages. To consider RMSE by different pig growth stages, an RMSE for error rate is introduced as listed in Table 3.5. Other than the weight, feed intake, and backfat probe thickness using temporal observation, the current research applied the RMSE of error rate to the entire cycle performance including the average daily gain (ADG) and the feed conversion ratio (FCR). Based on the results, the simulation on weight had the most accurate result, and the simulation on backfat performs had the worst.

Table 3.5 Calibration root mean square for error rate

Indicators	RMSE for error rate
Weight	4.55%
Feed Intake	5.27%
Backfat	13.8%
ADG	5.58%
FCR	4.93%

Although the methods described above provide quantitative results for the model performance, they do not provide accuracy for each temporal observation. Figure 3.9 demonstrates the temporal RMSE error rate for pig live weight, feed intake, and backfat probe thickness. Based on the temporal RMSE of error rate, the feed intake tends to have a higher RMSE error rate when the pig is smaller. On the other hand, backfat tends to have high RMSE error rate throughout the growing cycle.

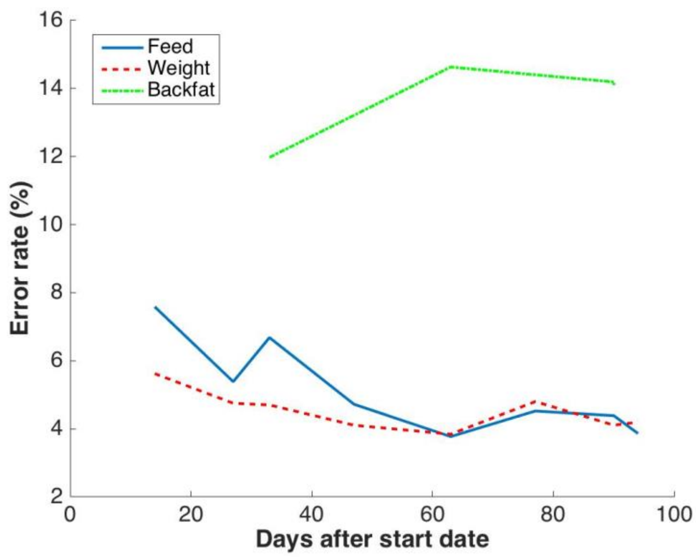


Figure 3.9 Temporal error rate on live weight, feed intake, and Backfat probe thickness in calibration

Other than the accuracy of the model, error distribution is also important to demonstrate the model performance. To visualize the temporal calibrated model performance on three indicators, Figure 3.10 to Figure 3.12 demonstrate side by side boxplot comparisons between simulated results and observations. In Figure 3.10, pig live weight estimation showed good modeling results but with a smaller variation than the observations.

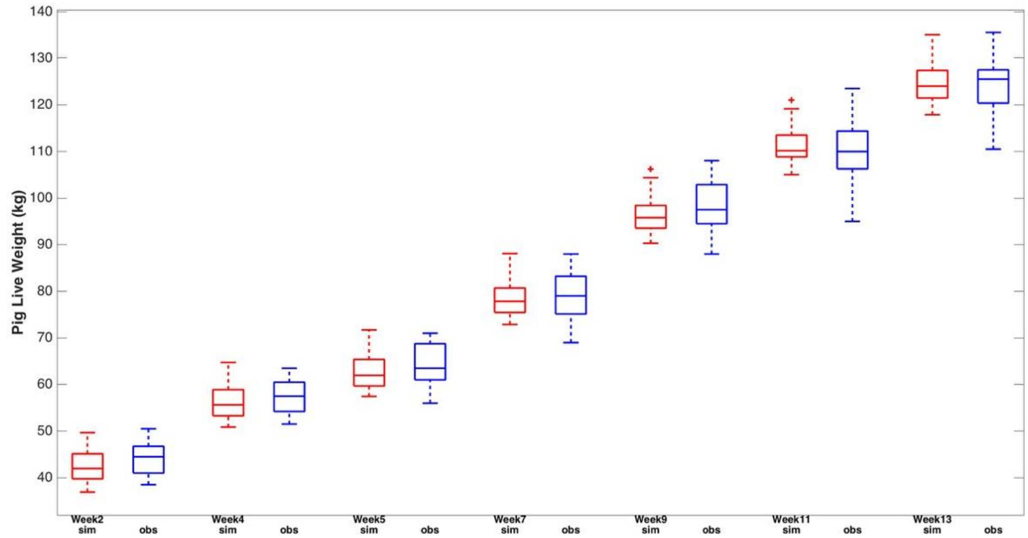


Figure 3.10 Comparison of simulated and observed pig live weight boxplot in calibration. The red boxplot denotes the simulation result (sim) and blue boxplot denotes the observation result (obs)

Daily feed intake simulation results showed an underestimation in the late growing stage in Figure 3.11.

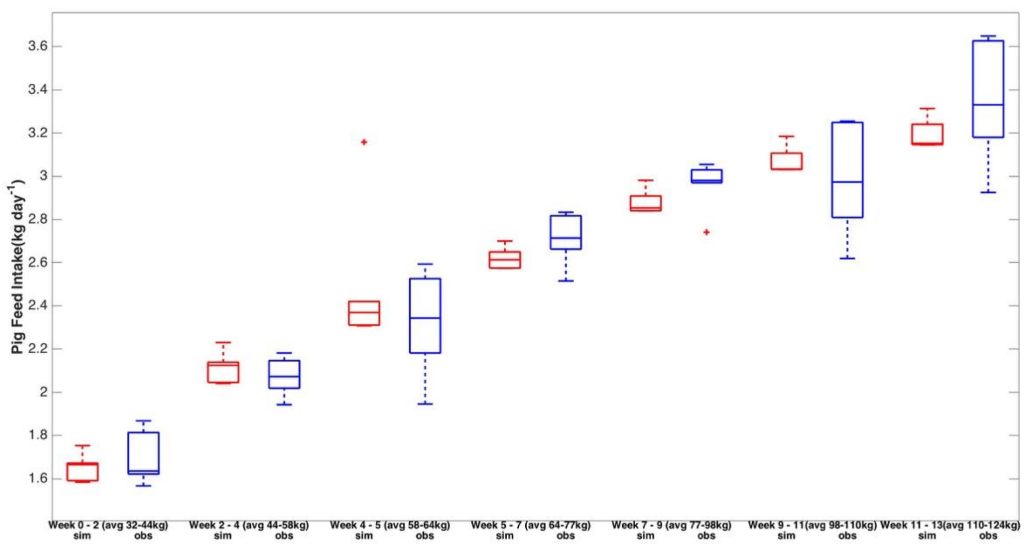


Figure 3.11 Comparison of simulated and observed daily feed intake boxplot in calibration. The red boxplot denotes the simulation result (sim) and blue boxplot denotes the observation result (obs)

Both the backfat probe thickness simulation and observation results were highly variated throughout the growing cycle as shown in Figure 3.12. The observation had a higher variation than the simulation results because of the individual swine growth variability.

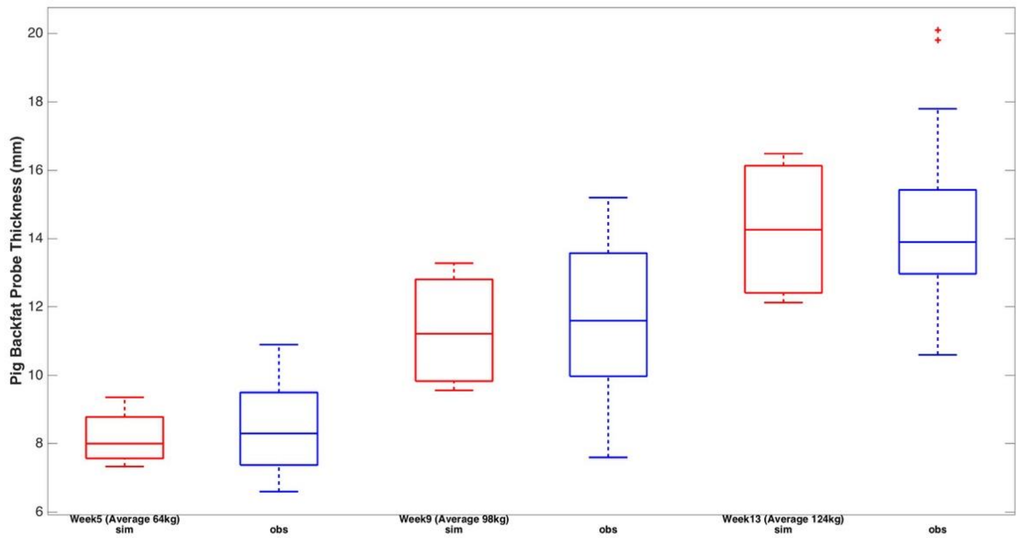


Figure 3.12 Comparison of simulated and observed backfat prove thickness boxplot in calibration. The red boxplot denotes the simulation result (sim) and blue boxplot denotes the observation result (obs)

The observed feed intake variation is larger than the simulation result because of the limitation of the MSPGM assumption. The MSPGM models only a whole barn performance and ignores individual variation. Because the model cannot estimate the competition and individual genomic variability, the simulation results tend to be more stable for the entire growing cycle.

3.3.2 Validation results

Based on the model calibrated from Experiment 1, this section presents and discusses the validation results based on Experiment 2. In Experiment 2, an individual swine grew significantly slower and was slaughtered for inspection. The reason for the slow-growing swine individual is still unknown. For validation purposes, the current research does not consider the pig live weight and backfat probe thickness as part of the validation process. Because feed intake information is recorded at the pen level, the pen that hosted the slow-growing individual swine was omitted for validation purposes.

The statistics for the regression results are listed in Table 3.6. All the slopes of calibration validation indicators were underestimated as shown in Figure 3.13 to Figure 3.15. Pig live weight simulation has the smallest standard error based on the standard error, which indicates a higher precision. Backfat probe thickness has the largest standard error for the slope estimation, indicating a weak precision. In general, the simulation results show an underestimation trend and higher RMSE compared to the validation data. The RMSE for the pig live weight is 6.45 kg. Feed Intake per pig has a higher RMSE at 13.1 kg. Backfat probe thickness shows a 2.56 mm RMSE.

Table 3.6 Validation result for regression and RMSE

Indicators	Slope	Standard Error	P value for Slope ≠1	RMSE
Weight	0.9685	0.0036	<0.0001	6.45 kg
Feed Intake	0.9094	0.0115	<0.0001	13.1 kg
Backfat Probe Thickness	0.8841	0.0155	<0.0001	2.56mm

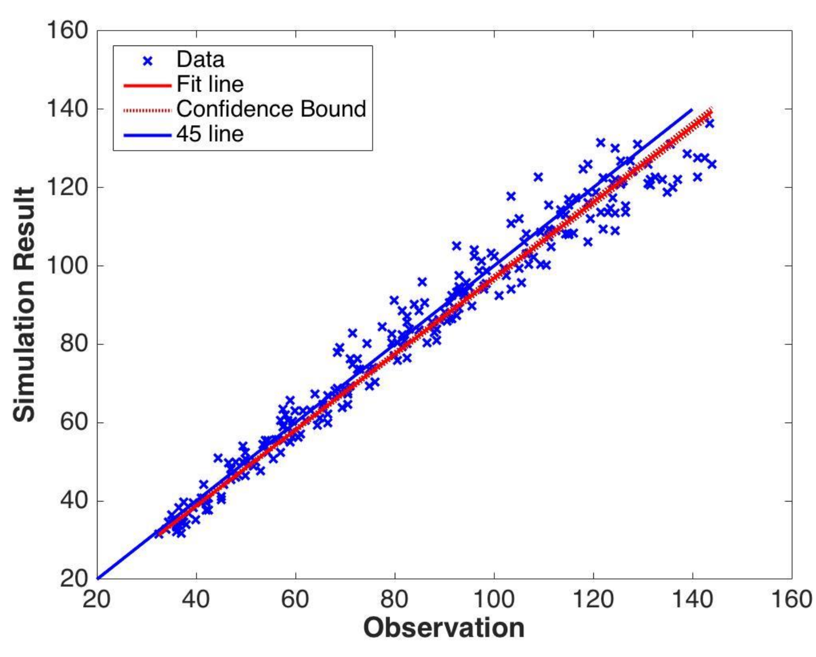


Figure 3.13 The validation regression of the simulation and observation for pig live weight (kg)

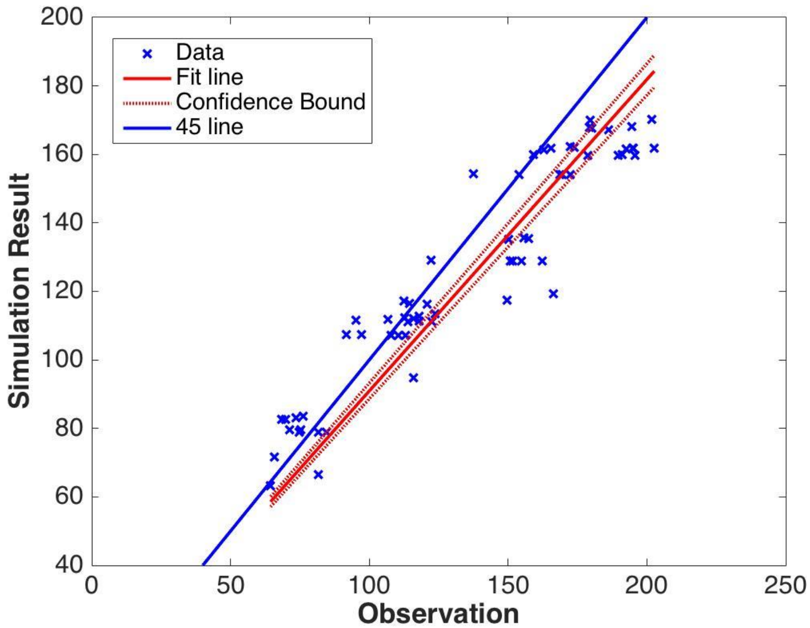


Figure 3.14 The validation regression of the simulation and observation for recorded feed intake (kg)

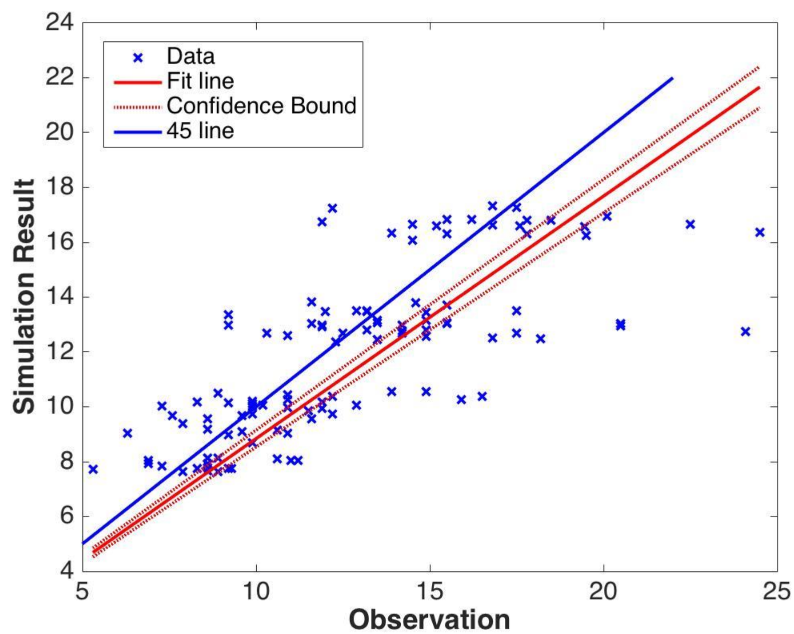


Figure 3.15 The validation regression of the simulation and observation for backfat probe thickness (mm)

The error histogram for the ADG shows an underestimation simulation result and a positive skew residual structure (Figure 3.16.a), and it leads to a positive skew residual structure in the FCR (Figure 3.16.b).

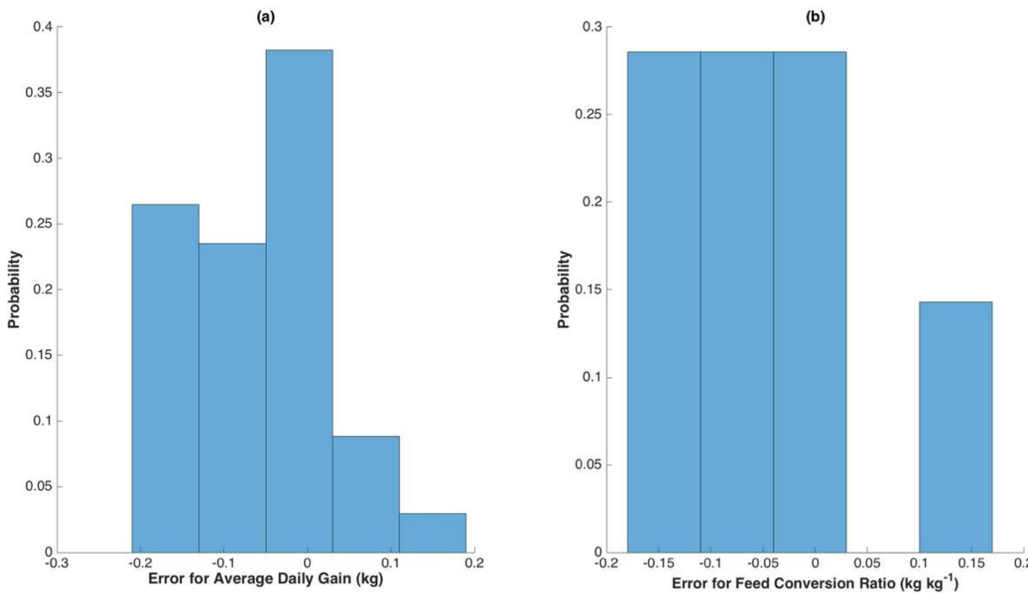


Figure 3.16 The histogram for error in validation (simulation - observation) for (a) average daily gain and (b) feed conversion ratio

The RMSE for the error rate of the validation process is shown in Table 3.7. Simulation of the FCR performs the most accurate result, and the simulation on backfat performs the worst.

Table 3.7 Validation root mean square for error rate

Indicators	RMSE for error rate
Weight	6.34%
Feed Intake	8.13%
Backfat Probe Thickness	18.6%
ADG	9.37%
FCR	4.21%

Figure 3.17 demonstrates the temporal RMSE error rate for pig live weight in the validation process, feed intake, and Backfat. Based on the temporal RMSE of error rate, the feed intake tends

to have a higher RMSE error when the pig is smaller. Backfat tends to have a high RMSE error throughout the growing cycle in the validation dataset.

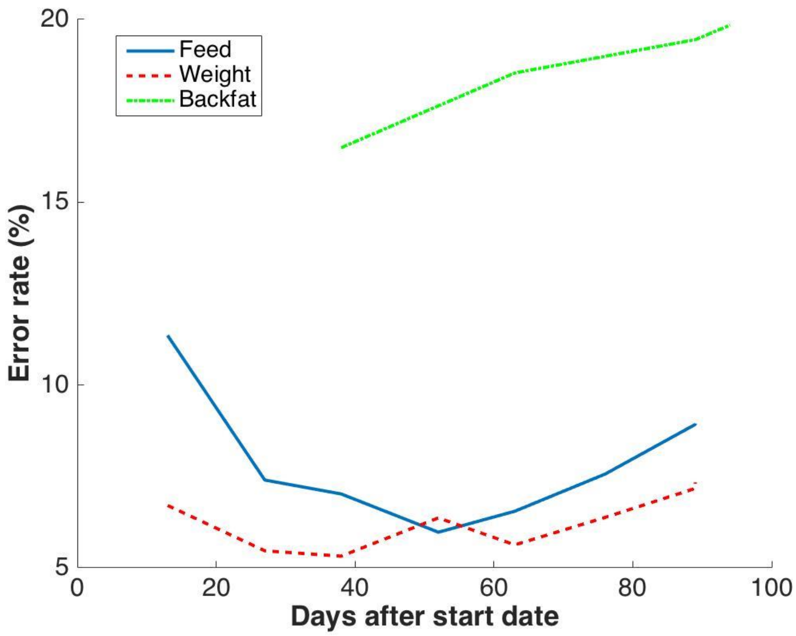


Figure 3.17 Temporal error rate on live weight, feed intake, and Backfat probe thickness in validation

Figure 3.18 to Figure 3.20 demonstrates side by side boxplot comparisons between simulated result and observations. Individual pig feed intake per day is underestimated from week 7 to week 9, and it leads to underestimation for pig live weight started from Week 9. The variation in the validation dataset is higher than the simulation results.

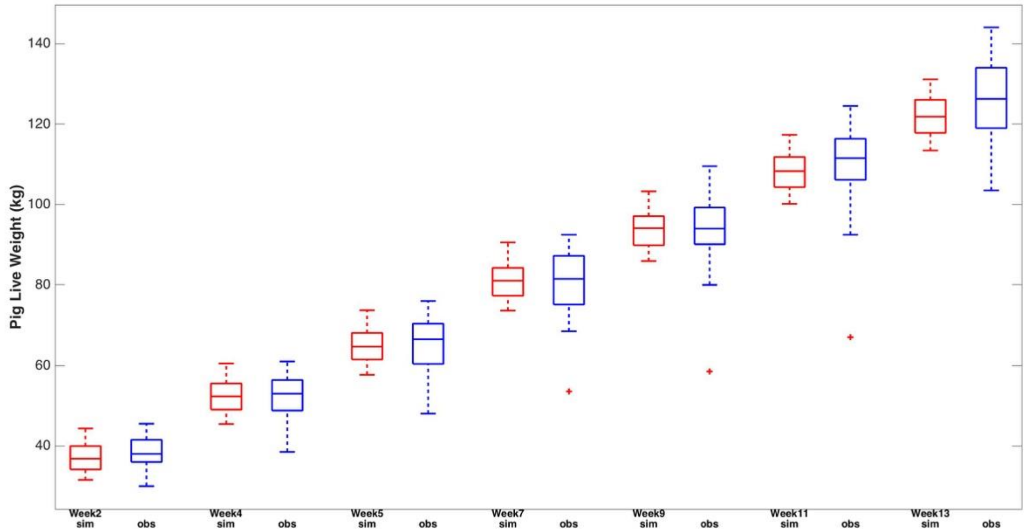


Figure 3.18 Comparison of simulated and observed pig live weight boxplot in validation process. The red boxplot denotes the simulation result (sim) and blue boxplot denotes the observation result (obs)

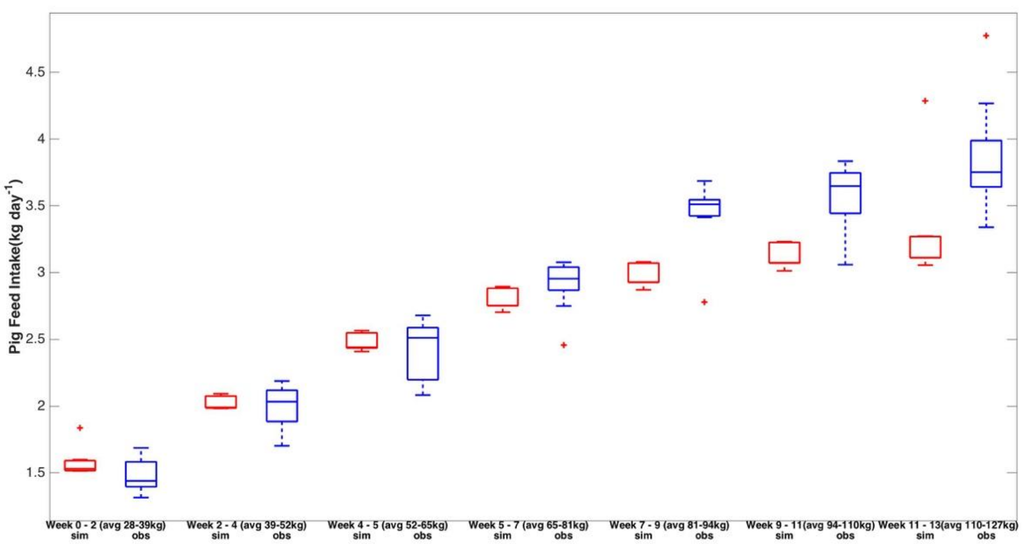


Figure 3.19 Comparison of simulated and observed daily feed intake boxplot in validation. The red boxplot denotes the simulation result (sim) and blue boxplot denotes the observation result (obs).

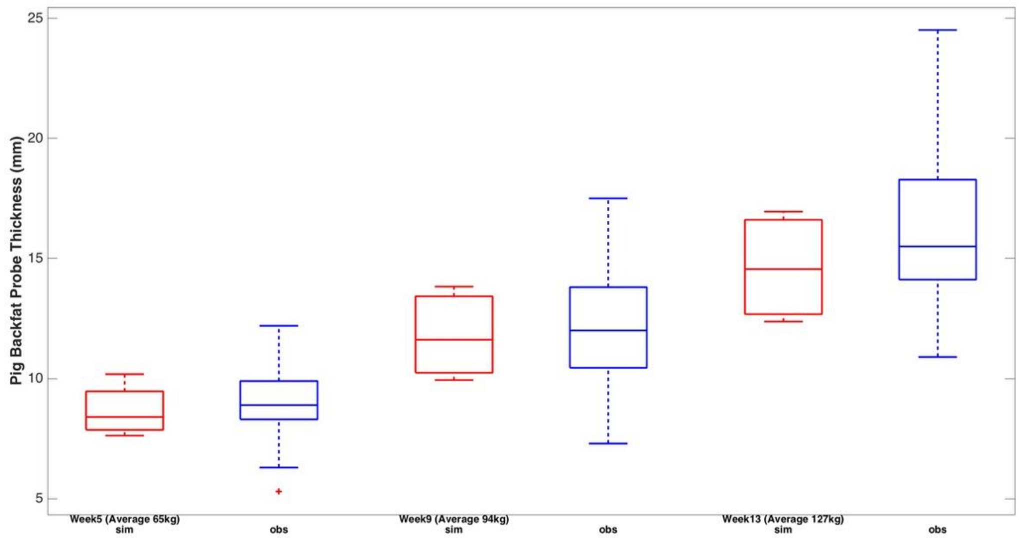


Figure 3.20 Comparison of simulated and backfat probe thickness boxplot in validation. The red boxplot denotes the simulation result (sim) and blue boxplot denotes the observation result (obs)

Temperature records in Experiment 1 are better to represent the indoor temperature because both the temperature sensors and the experiment pens during trials were located at the center of the room. By contrast, during Experiment 2, the trial pens were located on the side of the room but the temperature sensor was in the middle. During the cold outdoor temperature period, the recorded temperature may have been higher than the true swine growth environment temperature.

To modify the recorded temperature, the current research assumed 2°C temperature difference between the recorded temperature and the average room temperature on the side that was closer to the wall. The calibration curve performance improved as shown in Table 3.8.

Table 3.8 Validation with simulated temperature results for regression and RMSE

Indicators	Slope	Standard Error	P value for Slope ≠1	RMSE for error rate
Weight	0.9724	0.0036	<0.0001	5.5 kg
Feed Intake	0.9281	0.0110	<0.0001	12.1 kg
Backfat Probe Thickness	0.9070	0.0157	<0.0001	2.59 mm

Slopes for the all live weight, feed intake, and backfat probe thickness improved but were still underestimated as compared to Table 3.6. Both the precision for the pig live weight and feed intake improved based on the lower standard error. Table 3.9 shows improvements for all the indicators compared to Table 3.7. The results from Table 3.9 imply a more accurate indoor temperature that indicates the swine growth environment can improve the model results.

Table 3.9 Validation root mean square for error rate with modified temperature

Indicators	RMSE for error rate
Weight	6.24 %
Feed Intake	7.78%
Backfat Probe Thickness	18.3%
ADG	8.99%
FCR	4.01%

The high variability of observed growth performance is one of the reasons for a higher RMSE error rate in the validation process. Excluding pigs removed from the pen before achieving market-size, the observations in the validation dataset (Experiment 2) have higher weight and backfat probe thickness variation than observations in the calibration dataset (Experiment 1) as shown in Table 3.10. ADG between different pens also shows high variability in Experiment 2. The current research applied boxplot for the ADG in each pen in Experiment 2 as shown in Figure 3.21. The results of Experiment 2 show a stable ADG in Pen # 11, where a heater was located. Because the south side of the room for Experiment 2 opens frequently when the outdoor temperature is low, pens closer to the south side had a lower temperature. With the heater, Pen # 11 has potential to maintain the temperature, while other pens closed to south side have a lower temperature than designed. This result implies that a more appropriate environment can provide a more stable swine growth performance. More experiments on environmental effects on pig growth are required to statistically conclude the relationships.

Table 3.10 Performance variance of market-size pig

Performance Indicators	Experiment 1	Experiment 2
Weight (kg)	32.09	86.33
Cumulative Feed Intake(kg) per pig from week 11 to market size	169.9	154.17
Backfat Probe Thickness(mm)	7.698	11.16
ADG (kg/day)	0.0034	0.0097
FCR (kg/ kg)	0.0289	0.0178

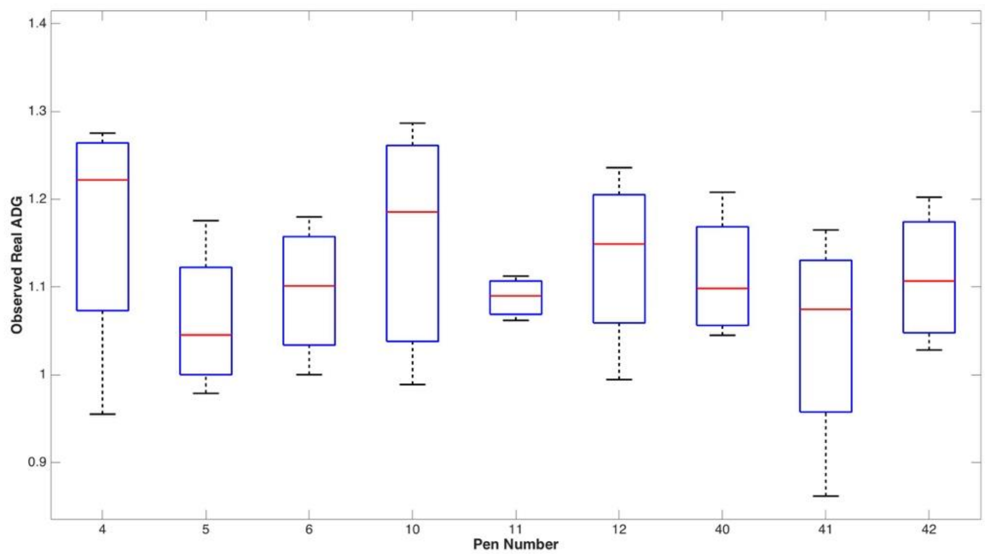


Figure 3.21 ADG in Experiment 2 in different pen

Overall, the model tends to underestimate the pig live weight and feed intake with a moderate error rate in the validation process. Backfat probe thickness, on the other hand, performs worse in both precision and accuracy. The discrepancy between simulated and observed backfat probe thickness is because of the model limitations of individual growth difference. Based on the calibration process, the model results imply that the energy requirements to deposit lipid and protein have not been updated for modern swine. More specific experiments are suggested to gain a better understanding of modern swine energy requirements on lipid and protein deposition.

The other limitation for the model calibration relies on the constant ratio to reference to maximum protein deposition rate rPd_{max}, which maintains the same shape compared to the Pd_{max}reference published by Black et al. (1987). A time-variated rPd_{max} may be applied for higher accuracy; however, the system might be overdetermined by too many variables and lose the purpose of the entire growing cycle calibration. Future research on modern swine Pd_{max} will be required to reduce the error rate for the nutrient partitioning scheme model.

3.4 Conclusion

The current research calibrated and validated the modified simple pig growth model (MSPGM) based on 2016 experiments with three indicators that were observed in a time series: pig live weight, feed intake, and backfat probe thickness. The simulation result in the feed intake and live weight is more accurate and precise than for the backfat probe thickness. Simulation results for calibration tend to underestimate the feed intake and backfat probe thickness. Pig live weight simulation has the highest precision and accuracy among three indicators. The backfat probe thickness simulation result tended to have both the lowest accuracy and precision. Validation was performed based on calibrated parameters. The model tended to underestimate all three indicators and had a lower precision compared to the calibration dataset potentially due to the overestimated recorded temperature. The real temperature of each pen was estimated based on the recorded temperature and was performed to the validation data. The validation model accuracy and precision were improved but the model still underestimated all three indicators. This calibration and validation section implied that the modified MSPGM tends to underestimate the pig growth performance, especially for cooler and unstable environment temperatures.

CHAPTER 4: A SYSTEM SIMULATION APPROACH FOR ESTIMATING THE INTEGRATED EFFECT BETWEEN SWINE GROWTH PERFORMANCE AND SWINE BARN MANAGEMENT: A DYNAMIC MODEL AND ITS SENSITIVITY ANALYSIS

4.1 Introduction

Commercial grow-finish swine facilities that are mechanically-ventilated raise pigs from 30 kg to market size in the same house require dynamic environmental conditions and complex feed management. Most existing swine house facilities currently have environmental controls based on the setpoint temperature suggested by industry that aims to shorten the growing period. However, the relationship between housing management and swine production performance is not well understood. To investigate the integrated effects of indoor environment control and housing management on swine growth performance, it is necessary to examine their interrelationship.

Swine growth is strongly affected by the indoor environment of the barn. The relationships among indoor air temperature, nutrients, and efficiency of live weight gain have been quantified by several studies. Moughan, Smith, and Pearson (1987) developed a simple pig growth model for the grow-finish period of swine production to describe pig live weight changes on a daily basis. Unlike Black, Fleming, and Davies (1987) who applied empirical relationships between parameters to determine nitrogen retention, Moughan et al. (1987) constrained body protein retention by requiring a minimum level of body lipid. The Moughan model showed accurate predictions with few parameters but did not take into account environmental factors. Black et al. (1987) developed a model (AUSPIG) that simulates the entire productive cycle and includes predictions of the *ad libitum* effect by regarding nutrition, genetics, and environment. Researchers

(Bridges, Turner, Stahly, Usry, & Loewer, 1992; Bridges, Turner, Usry, & Nienaber, 1992; Usry, Turner, Bridges, & Nienaber, 1992) in the U.S. developed a model (NCPIG) based on the interaction among environmental factors, feed intake, and genotypes. That model also predicted how *ad libitum* intake influences pig growth. However, the full NCPIG model is difficult to use due to its complicated parameters.

Swine barn management is strongly affected by internal loads from swine heat and moisture production. Researchers have measured heat and moisture production and developed livestock heat production models that include levels of animal activity, swine live weight, and the environment around them. These models showed accurate estimations based on research experiments and are used as references for swine barn management (Albright, 1990; Brown-Brandl, Nienaber, Xin, Gates, 2004; Pedersen & Sallvik, 2002).

Strategies for heating and ventilation systems in swine housing have been simulated by many researchers. Lambert, Lemay, Barber, Crowe, and Chénard (2001) compared different kinds of control systems by assuming linear pig growth performance inside the barn. Morsing, Pedersen, Strøm, Jacobsen (2005) also simulated indoor psychrometric properties and swine house energy consumption according to swine heat and moisture production based on Danish recommendations for growing pigs. While these studies provided insight for different types of swine barn management, they did not consider pig growth performance relative to the swine barn indoor environment.

Although swine barn management simulations and pig growth models are mature, few studies have connected the two together. Bridges, Turner, and Gates (1998) connected NC-204 swine growth model (NCPIG) and natural-ventilated swine barn simulations to evaluate economic returns of misting-cooling systems. The same research group compared the NCPIG model with results from an on-farm experiment and found the predictions were accurate (Turner et al., 1998).

The introduction of modern mechanical ventilation control systems now require a new model with only a few parameters that connect a pig growth model to a mechanical-ventilated swine barn simulation for the purpose of showing how mechanical-ventilated operation strategies affect swine production.

In order to evaluate the integrated effect, several performance indicators were selected for this simulation to represent the total system performance. The feed conversion ratio (FCR) is especially important to integrated producers because feed is one of the major costs for swine production. Higher average daily gain (ADG) demonstrates a potential higher profit for the swine producer due to a higher rate of turnover. The average energy utility cost (AEUC) for the entire growing period is also important for swine producers. However, there is a trade-off between the AEUC and ADG. A larger ADG implies more energy intense swine barn management needed to maintain a comfortable indoor environment that, in turn, may lead to higher utility costs. In order to consider both the ADG and AEUC, a marginal utility cost (MUC) is introduced in this new model to present the marginal effect on AEUC as defined by the daily average energy utility cost per average daily gain (AEUC ADG^{-1}).

The overall goal of this present study is to quantify the integrated effect between swine barn management and swine growth performance under different season conditions, including daily average energy utility cost for swine housing (AEUC), average daily gain (ADG), marginal utility cost (MUC, AEUC/ADG) and feed conversion ratio (FCR). The specific objectives are to develop an integrated dynamic swine growth and swine barn model, to evaluate the integrated swine production model, and to identify the influential model parameters with sensitivity analysis.

4.2 Materials and Methods

4.2.1 Model overview

A systematic diagram of the integrated swine production system model (ISPSM) is shown in Figure 4.1. The Modified Simple Pig Growth Model (MSPGM) that generates swine live weight and metabolizable energy intake estimation is used as an input variable for the swine barn energy consumption model (SBECM). The SBECM simulates indoor temperature (°C) and dynamic heat/power requirements (W) based on a defined control strategy. The indoor temperature generated from the SBECM is an input variable in MSPGM. The average energy utility cost (AEUC, \$) is calculated by a Utility Cost Module (UCM) based on an assumed price for natural gas and electricity as well as the energy consumption from SBECM. All dash blocks in the systematic diagram represent input variables for the proposed ISPSM. The average energy utility cost (AEUC, \$), feed conversion ratio (FCR), average daily gain (ADG, kg), and marginal utility cost (MUC ADG^{-1}, \$ kg^{-1}) are the outputs of ISPSM developed for future sensitivity analysis.

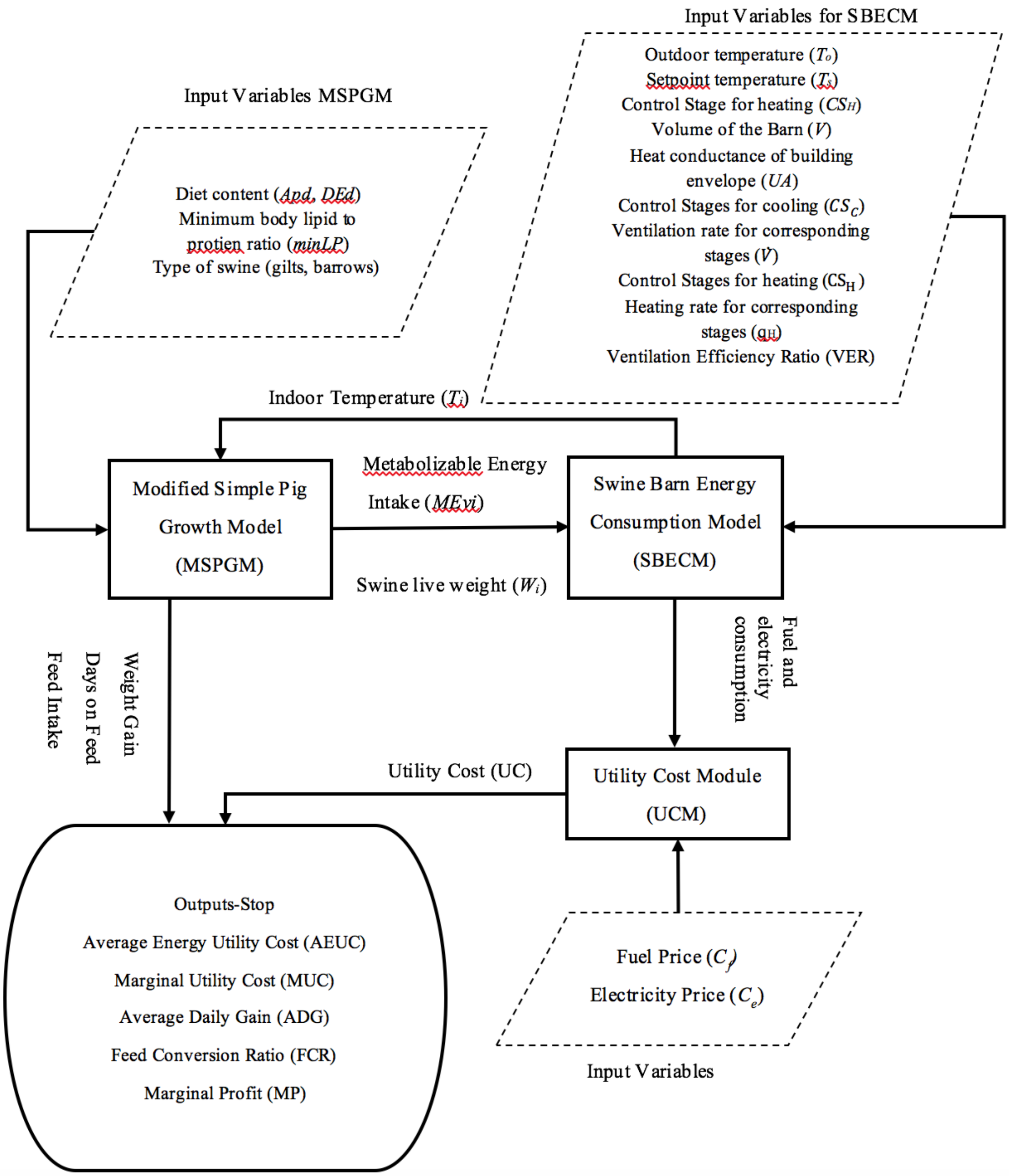


Figure 4.1 The Systematic Diagram of the Integrated Swine Production System Model (ISPSM) scheme. Based on input variables for MSPGM, MSPGM simulates daily live weight and metabolizable energy intake, which are taken as inputs for the SBECM. The SBECM calculates indoor temperature based on several SBECM input variables. The calculated indoor temperature has a direct effect on the MSPGM simulation. The UCM calculates utility cost based fuel and electricity consumption. The final ISPSM output includes average energy utility cost, marginal utility cost (average energy utility cost per weight gain), average daily gain, and feed conversion ratio (feed weight per live weight gain).

4.2.2 Model development

4.2.2.1 Modified simple pig growth model (MSPGM)

The current study applies the modified simple pig growth model (MSPGM) described in Chapter 3. The MSPGM, which follows the simple pig growth model (SPGM) scheme developed by previous research (De Lange, 1995; Moughan et al., 1987), was selected for its simplicity. Data recorded from two individual experiments with the same breeding line but with different indoor temperatures was applied for calibration and validation processes. More details of the calibration – validation process are addressed in Chapter 3.

Based on the results in Chapter 3, the MSPGM showed higher accuracy for weight and feed intake, but underestimated the backfat probe thickness. While the backfat probe thickness estimation result is not as accurate, the model utilizes only the pig live weight and feed intake as input from other subsystems. The seasonality would be more obvious for observation with regard to swine growth performance because the MSPGM underestimated of pig growth during a cooler indoor temperature range.

4.2.2.2 Swine barn energy consumption model (SBECM)

The algorithm proposed to calculate the energy consumption considers the content of swine diet, the ventilation rate, space heater capacities, and heat generated by occupants (pigs). The information gathered from the literature (i.e., building characteristics, swine type and equipment inventory) were used to develop the model. The objective of this section is to simulate swine barn energy consumption (both heat and electrical power usage) as part of the swine production process by applying the MSPGM to simulate swine heat production.

Heat transfer in a building in the proposed model is based on the control volume approach used and only the heat transfer across the building envelope was examined (Albright, 1990). The control volume for energy and mass balance is bounded by the building envelope. Simplified assumptions are as follows: 1) Attic temperature is the same as the ambient temperature. 2) There are no radiation heat fluxes between the interior surfaces and occupants. 3) Indoor air is complete mixed, which implies temperature transfer is spontaneous. Although these assumptions introduce errors to the model, only few model parameters are proposed by this study to simplify the computational processes.

Based on the information about building characteristics, occupants (grow-finish swine), heat production, and swine barn control strategies, the model proposed by this study involves an environmental simulation to estimate heat and electricity consumption for a swine barn.

The general dynamic mathematical model for indoor temperature T_i(°C) is based on a sensible heat balance:

$$\rho_{\bar{a}} C_P V \frac{dT_i}{dt} = (q_p + q_H - q_B - q_F) \tag{4.1}$$

where q_p (W) is the total sensible heat generated by pigs, q_H (W) is the heat generated by fuel heaters, q_B (W) is the building envelope heat loss, q_F (W) is the ventilation heat loss, t (day) is time, $\rho_{\bar{a}}$ (kg m^{-3}) is the air density, V (m^3) is the volume of the barn, and C_p (J kg^{-1} °C^{-1}) is the specific heat of the air.

Based on Brown-Brandl et al.(2004) and Pedersen & Sallvik (2002), the following equations were used in the current study to determine heat (total and sensible) generated by the pigs. The previous studies noted that pig live weight, ambient temperature, feed intake, and animal activity had a significant impact on heat production.

$$\Phi_{tot} = 5.09W^{0.75} + (1 - (0.47 + 0.003\,W))(MEvi \times 0.011574 - 5.09W^{0.75}) \tag{4.2}$$

where Φ_{tot} is the total heat production at 20°C, W is the pig live weight (kg), and $MEvi$ is the feed energy intake (kJ d^{-1}). For temperatures different from 20°C, the temperature modified total heat production Φ^*_{tot} can be calculated by indoor temperature T_i

$$\Phi^*_{tot} = \Phi_{tot} + 0.012\Phi_{tot}(20 - T_i) \tag{4.3}$$

The sensible production is determined by

$$\Phi^*_{sen} = 0.62\Phi^*_{tot} - 1.15 \times 10^{-7}T_i^6 \tag{4.4}$$

where the Φ^*_{sen} is the sensible heat production

Because there is no measured animal activity data available, a single sinusoidal model that simulates diurnal variation of animal activity, was used based on (Pedersen & Sallvik, 2002).

$$A = 1 - a \times sin\left(\frac{2\pi}{24}(h + 6 - h_{min})\right) \tag{4.5}$$

where h is the current hour, h_{min} is the hours that the minimum activity occurs, a is the activity variations for pigs.

The total pig sensible heat production q_P is then defined by

$$q_P = A\ \times \Phi^*_{sen} \tag{4.6}$$

The minimum activity was assumed to occur at 0:40 am (h_{min}=0.68) and the diurnal variation for pigs was approximately 31% (a=0.31) (Blanes & Petersen, 2005). Thus, the hourly correction factor for animal heat production can be calculated and modified by diurnal variations of heat production generated by pigs.

Heat loss q_b (W) through building envelope is determined by

$$q_b = UA(T_i - T_o) \tag{4.7}$$

where UA (W °C^{-1}) is the total conductance of the barn and T_o (°C) is the outdoor temperature. Heat loss through ventilation fans q_F(W) can be described as:

$$q_F = \rho \dot{V} C_P^a (T_i - T_o) \tag{4.8}$$

where $\dot{V}$ (m^3 s^{-1}) is the ventilation rate.

Based on the ventilation rate, stage operation on exhausted fan control was applied to calculate energy consumption P_F (W).

$$P_F = \frac{\dot{V}}{VER} \tag{4.9}$$

where VER is the fan efficiency (m^3 s^{-1} W)

Other than ventilation electricity consumption, lighting is also a major part of electricity consumption. MWPS-28 Wiring Handbook suggests 55 lux for grow-finish lighting (daytime) and estimates 0.57 watts per square foot for 100-watt incandescent bulbs (MPS, 2005). The lighting schedule is from 6 am to 2 pm. This study utilized the Handbook information to estimate electricity usage for light. Most of the total electric consumption is used for ventilation fans and lights; therefore, the current study used only lighting and ventilation power requirements and assumed other power consumption was negligible.

Based on the equations above, this study built an energy consumption model based on the model structure proposed by Chao et al. (2000). Stage control based on setpoint temperature was implemented in the current research. When the indoor temperature is higher than the setpoint temperature, ventilation is used to cool down the indoor environment. When the indoor temperature is lower than the setpoint temperature, the heater will heat up the indoor environment. More model structure details can be found in the mode proposed by Chao et al. (2000).

Since the MSPGM is a discrete model but indoor temperature is simulated continuously, this study assumed the critical indoor temperature (T_i^C, °C) for swine growth is the daily average temperature. The daily pig live weight, feed, and heat production were taken as constants for the day for the dynamic SBECM.

4.2.2.3 Utility Cost Module (UCM)

Based on the swine barn energy consumption model, this study calculated the gas utility cost U_G by assuming constant fuel cost C_f (\$ m^{-3}) and a 95% efficiency:

$$U_G = \int_{t=start\ of\ season}^{t=End\ of\ season} q_H dt \div HV_{natural\ gas} \times C_f \div 0.95 \tag{4.10}$$

where $HV_{natural\ gas}$ is the heating value of natural gas that is assumed to be 3.67 x 10^7 (J per m^3). The electricity utility cost U_E is as follows:

$$U_E = \int_{t=start\ of\ season}^{t=End\ of\ season} (P_F + P_L) dt \div 3600 \div 1000 \times C_e \tag{4.11}$$

where P_L (W) is the power consumption for light. C_e (\$ kWh^{-1}) is the cost for electricity. The average energy utility cost AEUC is the average of electricity utility cost and gas utility cost:

$$AEUC = \frac{U_G + U_E}{l_{cycle}} \tag{4.12}$$

where l_{cycle} is the length of the growing period

4.2.3 Location and model input

A case study of this model was conducted for a virtual swine barn in Ames, Iowa, in 2013, because Iowa is one of the major swine production states in the U.S. The city of Ames is in the middle of Iowa and has a comprehensive weather dataset for conducting the case study.

In 2013, the outdoor temperature in Ames was low in the winter while the outdoor temperature was high in the summer as shown in Figure 4.2. These weather characteristics provided a valuable platform to demonstrate the effect of swine barn management during both cooling and heating seasons. Hourly meteorology data were retrieved from Iowa Environmental Mesonet (IEM) to represent outdoor temperature.

All input variables for the integrated swine production system model are listed in Table 4.1. Bold input parameters are vectors including multiple elements. A designed stage control for a virtual swine barn with 2400 heads is shown in Table 4.2 for this study. Different stages of the ventilation rate and the heating rate were performed based on the difference between the setpoint temperature and the indoor temperature. The corresponding indoor setpoint temperature suggested by Prairie Swine Centre (2000) is shown in Table 4.3.

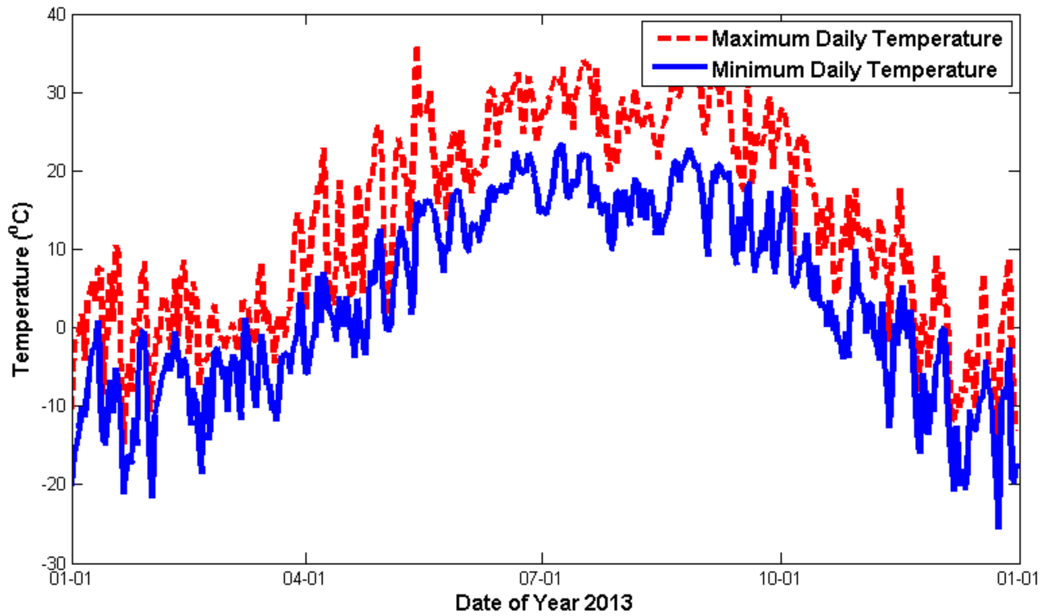


Figure 4.2 Maximum and minimum daily outdoor temperature of Ames, Iowa in 2013

Table 4.1 Model parameter description

Parameter	Description	Unit
UA	Heat Conductance for Building Envelope	W °C^{-1}
rAPd	Ratio of available protein in diet compared to *control diet* Table 3.1	NA
minLP	Minimum Lipid to Protein Ratio	NA
MEd	Metabolizable energy in diet	kJ
Type	Types of swine: barrows/gilts	NA
Ts	Setpoint Temperature	°C
T_o	Outdoor Temperature	°C
C_e	Electricity Price	¢ per kWh
C_f	Fuel Price	$ per 1000 ft^3
V	Volume of the Barn	m^3
N	Number of Swine	Head
M_{FI}	modification factor for feed intake	NA
$\boldsymbol{\dot{V}_S}$	Ventilation Rate for Corresponding Stages	m^3 s^{-1}
$\boldsymbol{CS_V}$	Control Stages for Ventilation	°C
$\boldsymbol{VER}$	Ventilation Efficiency Rate	m^3 s^{-1}W^{-1}
$\boldsymbol{q_{HS}}$	Heating Rate for Corresponding Stages	W
$\boldsymbol{CS_H}$	Control Stages for Heating	°C

Vector type parameters are in bold font

Table 4.2 Stage control for ventilation fans and heaters

Heating/ Cooling	Difference between setpoint and indoor temperature	Details of stages		
Ventilation system	Ventilation rate stages	Ventilation rate (m^3 s^{-1})	Size and Number of Fans	Average Ventilating Efficiency Ratio, VER (m^3 s^{-1} W^{-1})
	0	9.83	16" x 6	5.76×10^{-3}
	2	19.83	16" x 6 +36" x 2	7.66×10^{-3}
	4	29.84	16" x 6 +36" x 4	8.29×10^{-3}
	6	51.36	16" x 6 +36" x 4+48" x 2	8.65×10^{-3}
	8	94.40	16" x 6 +36" x 4+48" x 6	8.88×10^{-3}
	10	137.44	16" x 6 +36" x 4+48" x 10	8.97×10^{-3}
Heater	Heating rate stages	Heating rate (W)		
	0	0		
	-2	59 k		
	-4	118 k		
	-6	177 k		

Table 4.3 Industry recommended setpoint temperature for heating and cooling seasons

Single pig live weight (kg)	Setpoint temperature for the Heating Season (°C)	Setpoint temperature for the Cooling Season (°C)
25	21	22
30	20	21
35	19	19
40	17	18
45	16	17
50	15	16
55	14	16
60	14	16
70	14	16
80	14	16
90	14	16

4.2.4 Sensitivity analysis

In order to examine the sensitivity of parameters in different seasons, two different scenarios were designed. The first scenario was designed to raise the gilts from 33 kg to 130 kg (market size) in a commercial scale (2400 heads per barn) grow-finish facility in the 2013 heating season (from January 1st to March). The second scenario was designed to raise the gilts from 33 kg to 130 kg in the same barn in the 2013 cooling season (from May 1st to October).

To evaluate the impact of parameters in the integrated model, this study conducted a global sensitivity analysis for the model. Fourier amplitude sensitivity testing (FAST) was implemented to estimate the global sensitivity index due to the model's non-linear characteristics. For sensitivity analysis, the range of parameters, including the setpoint temperature, the maximum protein deposition rate, diet content (corn percentage of Corn-SBM diets), electricity price, fuel price, and swine barn insulation are listed in Table 4.4. The values of other input parameters are also listed in Table 4.4.

The global sensitivity analysis toolbox (GSAT) in Matlab was implemented for the purpose of evaluating the sensitivity of the parameters. A search curve of the perturbed parameter set was designed for the FAST analysis. Around 1000 swine production performance indicator (ADG, AEUC, MUC, and FCR) results were simulated with different parameters of each season for the sensitivity analysis. The global first order sensitivity coefficient was used to describe the total sensitivity effect of the model, as follows:

$$TSI = \frac{V_i}{V_{total}} \tag{3.20}$$

where TSI is the total sensitivity index, V_i can be calculated by Fourier expansion and is the indicator output's variance of ith perturbed parameter, and the V_{total} is the total variance of the output (Cannavó, 2012).

Table 4.4 Parameter perturbation for sensitivity analysis. The referenced value for perturbed parameters are listed in brackets

Parameter	Value	Unit
UA	559.4 – 839.2, (699)	W °C^{-1}
rAPd	79% – 110%, (100%)	NA
minLP	0.8 – 11.2 (0.9%)	NA
MEd	Control Diet in Table 3.1	NA
Type	Gilts	NA
Ts	-3 to – 3 compare to Table 3.4 (0)	°C
$\boldsymbol{T_o}$	Heating Scenario: from Jan. 1st , 2013 to Mar. 2013 Cooling Scenario: from May 2nd , 2013 to Oct. 2013	°C
C_e	9.66 x 10^{-2} – 1.17 x 10^{-1} (0.1)	\$ kWh^{-1}
C_f	0.251 – 0.354 (0.30)	\$ m^{-3}
V	3995	m^3
N	2400	Head
M_{FI}	1	NA
$\boldsymbol{\dot{V}}$	[9.83 19.83 29.84 51.36 94.40 137.44]	m^3 s^{-1}
$\boldsymbol{CS_C}$	[0 2 4 6 8 10]	°C
VER	[5.76 7.66 8.29 8.65 8.88 8.97] x 10^{-3}	m^3 s^{-1} W^{-1}
$\boldsymbol{q_{HS}}$	[0 59 118 177]	kW
$\boldsymbol{CS_H}$	[0 -2 -4 -6]	°C

Vector type parameters are in bold font

4.3 Results and Discussion

Table 4.5 shows the total sensitivity indices (TSI) of swine production indicator including ADG, average energy utility cost (AEUC) for entire growing cycle, feed conversion ratio (FCR), and marginal utility cost (MUC) for different perturbed parameters. The TSI is an index between 0 and 1. The swine production performance indicator was more sensitive with regard to the parameters if the parameter's TSI was closer to 1. On the other hand, the indicator was less sensitive with regard to parameters if the parameter's TSI was closer to 0.

The electricity price (C_e) was more influential to the AEUC in the cooling season, and the fuel price (C_f) was more influential to the AEUC in the heating seasons as shown in Table 4.5. While the trend was as expected, the fuel price C_f was not the major contribution for the average energy utility cost fluctuation in the heating season because of the stable price range. In the cooling season, C_e was one of the major parameters that explains the average energy utility cost fluctuation. This result demonstrates the importance of electricity usage, contributed mainly by ventilation fan operation to the average energy utility cost. The building envelope heat conductance (UA) had only a tiny effect on all four performance indicators in both seasons although it had a direct effect on the swine barn thermal model. This result may have come from high thermal resistance and limited perturbation for UA. All of the above model parameters that describe the swine barn characteristics showed their influence on performance indicators; however, those characteristics explain only partial variance.

For swine barn management, the setpoint temperature was more influential for AEUC in the heating season compared to the cooling season due to a more achievable indoor setpoint temperature in the heating season. The setpoint was more influential on the marginal utility cost (MUC) in the heating season compared to the cooling season for the same reason. The setpoint was one of the major factors for both MUC in both seasons. This demonstrates the importance of the control strategy for swine growers who are concerned about utility per unit weight gain in both the heating and cooling seasons. Moreover, the setpoint has higher TSI of the ADG in the cooling season because of the lower TSI score for the *minLP* in the cooling season. Although the setpoint temperature is more achievable in the heating season, swine still grow even when the setpoint is 3°C higher than the reference in the cooling season. On the other hand, 3°C higher temperature than the reference in the cooling season may introduce heat stress and affect ADG. The higher setpoint TSI for the FCR in the heating season implies the potential to control the setpoint for different FCR in the heating season.

In the heating season, the *minLP* was very influential to the ADG. Because *minLP* represents swine biological potential of the lean ratio, a comfortable indoor environment without heat stress may maintain optimum growth, which is constrained by the *minLP*. The *minLP* is more influential to the FCR in the heating season compared to the cooling season for the same reason.

On the other hand, *minLP* is not influential for AEUC because it does not directly affect the utility cost. Available protein in the diet (*APd*), has a critical effect on ADG and FCR. Protein level in the diet is more sensitive in the cooling season compared to the heating season. When the indoor temperature is high, the swine tends to consume less diet. The critical level of overall protein intake is a potential reason that *APd* has higher TSI in the cooling season.

Based on the TSI in Table 4.5, the top three parameters that were most influential among all objectives were the maximum protein deposition rate (*minLP*), the available protein in diet (*APd*), and the setpoint temperature (*Setpoint*).

Table 4.5 Total Sensitivity Index (TSI) for the swine production system

Swine Production Performance Indicators	Electricity Price (*Ce*)	Fuel Price (*Cf*)	Heat Conductance (*UA*)	Set point	Minimum body protein to lipid ratio (*minLP*)	Available Protein in Diet (*APd*)
ADG in Heating Season	0.000	0.000	0.000	0.017	0.696	0.272
ADG in Cooling Season	0.001	0.000	0.000	0.240	0.404	0.313
AEUC in Heating Season	0.061	0.026	0.004	0.856	0.040	0.000
AEUC in Cooling Season	0.244	0.000	0.000	0.748	0.000	0.000
FCR in Heating Season	0.001	0.000	0.000	0.215	0.373	0.393
FCR in Cooling Season	0.003	0.000	0.001	0.004	0.328	0.606
MUC in Heating season	0.055	0.023	0.004	0.798	0.100	0.006
MUC in Cooling season	0.294	0.000	0.000	0.587	0.058	0.050

While the TSI can tell the absolute sensitivity index of a perturbed parameter, it does not show the trend for the parameter perturbation. The following session discusses the three main influential parameters with more detailed information. Each point in the following figures represents a simulation result with specific parameters. To better present the outcome, the current research shows referenced simulation result in each figure as a basepoint. Because of the searching curve sampling techniques for FAST approach, there might exists periodic patterns in the sensitivity analysis result. The following discussion aims to investigate the overall trend, but not specific patterns.

Minimum Lipid to Protein Ratio

minLP, which identifies the minimum body lipid to protein ratio, acts as a limitation on swine growth performance in the MSPGM and has a direct effect on ADG. When the *minLP* is lower, the ADG tends to be higher as shown in Figure 4.3.a. Due to the biological potential limitation, there exists an upper bound for ADG with different practices. A lower *minLP* performed for a shorter growing period by increasing the ADG, has no direct effect on daily average energy utility cost as shown in Figure 4.3.b. The same figure also demonstrates a higher AEUC in the cooling season compared to the heating season. Swine calibrated from Chapter 3 grow faster and produce more heat, therefore, the virtual swine barn in winter does not require too much heat for the entire space. On the other hand, the virtual barn in the cooling season needs to operate the ventilation fan more to compensate for the higher swine heat production. The marginal utility cost (AEUC ADG^{-1}) decreases because of the increased ADG as shown in Figure 4.3.c. The lower *minLP* implies a leaner pig, which requires less energy to deposit tissue; therefore, it has a lower FCR as shown in Figure. 4.3.d. In the cooling season, the range of the FCR tends to be greater than in the heating season because of the difficulties to achieve setpoint temperature. Because of leaner swine growth in the cooling season, the FCR may be lower under certain conditions. On the other hand, the FCR may be higher due to heat stress and insufficient energy and protein intake.

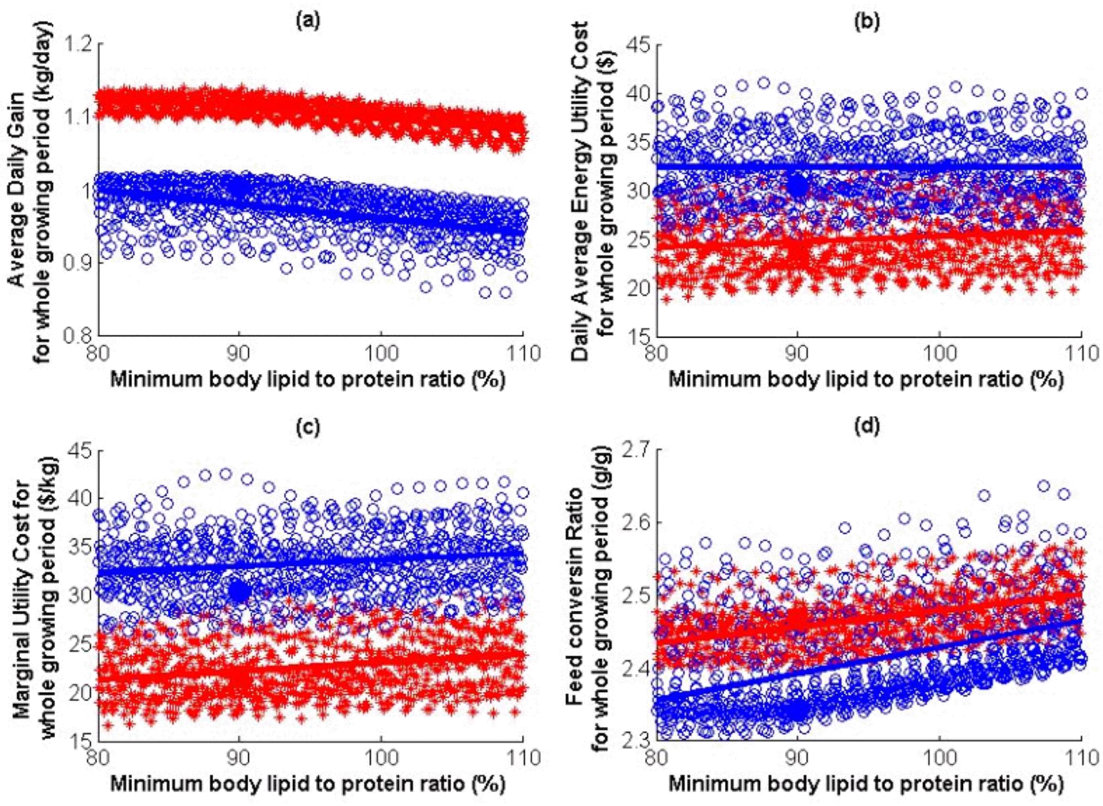


Figure 4.3 The sensitivity analysis for entire growing cycle with perturbed minimum body lipid to protein ratio with regards to (a) average daily gain (b) average energy utility cost (c) marginal Utility cost (d) feed conversion ratio. The red star and blue circle represents the simulation result with perturbed parameters in the heating and cooling season respectively. The red line represents the linear trend for the heating season. The blue line represents the linear trend for the cooling season. The square solid red and circle blue point represents the simulation result with referenced parameters for the heating and cooling season respectively.

Available protein in diet

Available protein in diet is shown in Table 4.5 to be a significant factor for all growth performance indicators. While the pig requires protein to build up lean tissue, lower protein diet content in the cooling season will inhibit the swine to grow as shown in Figure 4.4.a. However, if the protein level exceeds a certain amount in the heating season, the ADG will slightly decrease due to the energy cost for extra protein excretion. The ADG in the cooling season is lower than in the heating season due to heat stress in the cooling season. Figure 4.4.b shows a no trend on daily average energy utility cost (AEUC) with different *APd* in both seasons. AEUC is subject to the indoor thermal environment, and it is more closely related to the metabolizable energy intake than to the protein level in the diet. The decrease in ADG is due to the lower *APd* effect on the marginal utility cost (MUC) for the cooling season as shown in Figure 4.4.c. Because the *APd* does not show an apparent trend in either ADG or AEUC in the heating season, there is no apparent trend in the MUC in the heating season.

When the *APd* is high, the FCR is higher in the heating season compared to the cooling season. On the other hand, the FCR is lower in the cooling season when the *APd* is low. This seasonality implies that heat stress without sufficient protein intake will increase FCR in commercial swine barn. Because the FCR is more sensitive on *APd* in the cooling season, this research suggests feeding higher protein diet in the cooling season to mitigate the lower FCR in the cooling season due to heat stress and decreased feed intake.

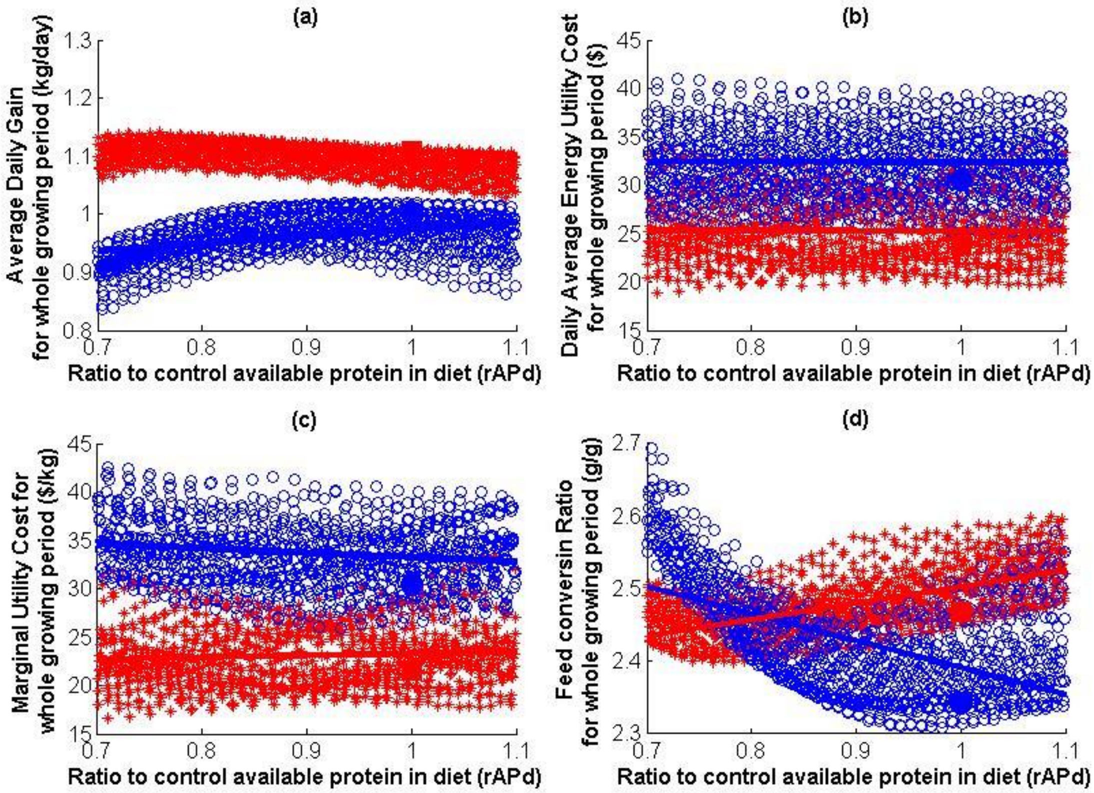


Figure 4.4 The sensitivity analysis for entire growing cycle with perturbed available protein in diet compared to control diet in Table 3.1 with regards to (a) average daily gain (b) average energy utility cost (c) marginal Utility cost (d) feed conversion ratio. The red star and blue circle represents the simulation result with perturbed parameters in the heating and cooling season respectively. The red line represents the linear trend for heating season. The blue line represents the linear trend for the cooling season. The square solid red and circle blue point represents the simulation result with referenced parameters for heating and cooling season respectively.

Setpoint temperature

Setpoint temperature is a direct factor for utility cost because the ventilation fan and heater operations are both based on the difference between the indoor temperature and the setpoint temperature. In both the cooling and heating seasons, when the setpoint tempearture is higher, the ADG tends to decrease due to the potential heat stress as shown in Figure 4.5.a. A generally higher ADG in the heating season is expected due to heat stress in the cooling season.

In Figure 4.5.b, the AEUC increases in the heating season while raising the setpoint tempearture but the AEUC decreases in the cooling season while also raising the setpoint temperature. In the cooling season, the higher setpoint temperature increases the average energy utility cost due to a higher fuel requirment. On the other hand, the higher setpoint temperature decreases the daily average energy utility cost due to a lower ventilation requirment. Marginal utility cost results (Figure 4.5.c) show a similar trend compared to the average energy utility cost due to AEUC differences. Without considering the disease effect, the lower setpoint temperature in heating season and higher setpoint temperature in the cooling season has better performance in marginal utiltity cost. To ensure swine growth under a healthy temperature range with the best marginal utility cost performance, a more comprehensive setpoint temperature suggested procedure is required to maximize the marginal utility cost savings. While swine have a lower metabolizable energy intake with higher indoor temperature, there is **no** specific trend for the FCR with higher setpoint temperature in the cooling season due to a nonachievable setpoint as shown in Figure 4.5.d. However, the FCR tends to decerase when the setpoint temperature is higher in the heating season. This indicates the potential reduction of the FCR in the heating season with better practices.

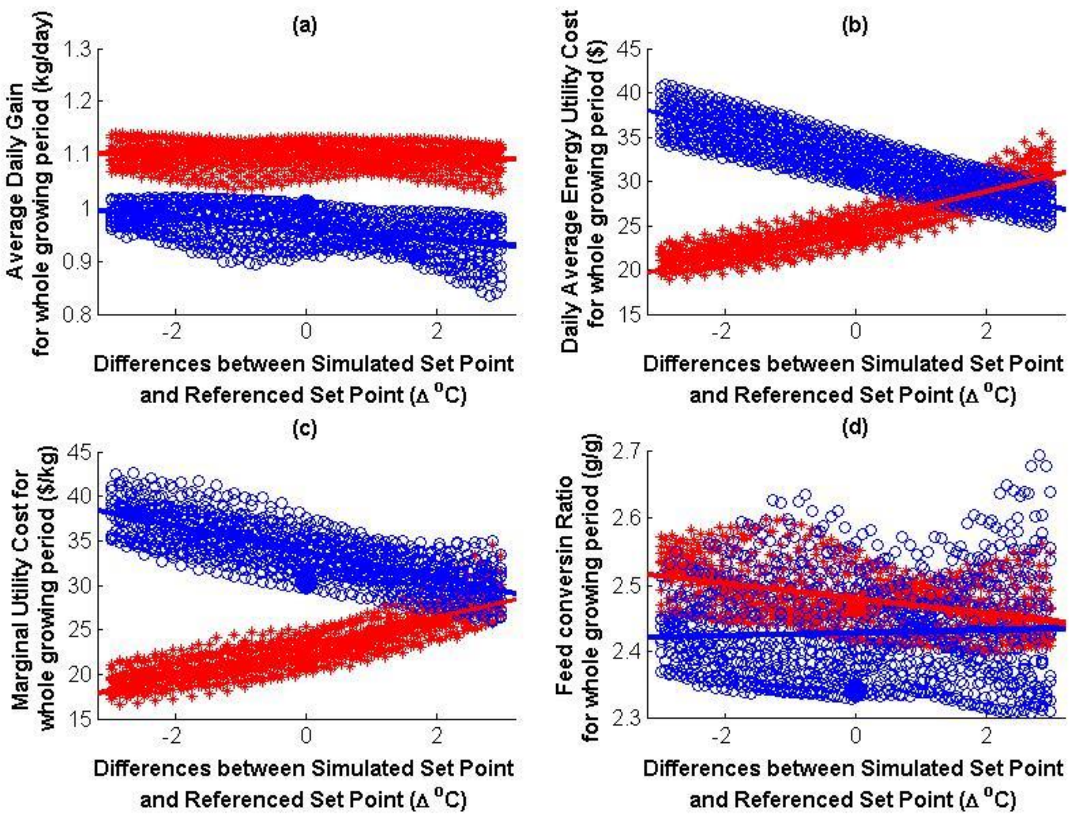


Figure 4.5 The sensitivity analysis for entire growing cc with perturbed setpoint temperature with regards to (a) average daily gain (b) average energy utility cost (c) marginal Utility cost (d) feed conversion ratio. The red star and blue circle represents the simulation result with perturbed parameters in the heating and cooling season respectively. The red line represents the linear trend for the heating season. The blue line represents the linear trend for the cooling season. The square solid red and circle blue point represents the simulation result with referenced parameters for heating and cooling season respectively.

4.4 Conclusion

A system computer simulation model was developed to predict the integrated effect of pig growth and swine barn management for a mechanically-ventilated grow-finish swine barn. The system model incorporated the interaction of growing performance that is subject to genetics, indoor environment, and diet content. A sensitivity analysis was applied to investigate the influential parameters for performance indicators such as average daily gain, feed conversion ratio, average energy utility cost, and marginal utility cost (average energy utility cost per average daily gain). The results show the importance of the protein level in diet, the setpoint temperature, and minimum body lipid to body protein ratio for all the swine production performance indicators. Leaner swine are beneficial for both ADG and FCR. The model result implies an optimum level of protein diet is beneficial for the ADG in both seasons. The sensitivity analysis results suggest feeding a sufficient protein diet, especially in the cooling season to prevent the higher FCR in the cooling season without sufficient protein. Based on the sensitivity analysis result, this research finds a positive correlated trend between setpoint temperature and the FCR in the heating season. This demonstrates the potential to control the setpoint to manage the feed conversion ratio. This model and its sensitivity analysis shows the capacity of investigating the integrated effect based on different scenarios and may be applied to other scenarios for future swine barn management.

CHAPTER 5: NUMERICAL ECONOMIC EVALUATION ON EVAPORATIVE COOLING PAD CONTROL TEMPERATURE OFFSET FOR MECHANICALLY-VENTILATED GROW-FINISH SWINE BARN

5.1 Introduction

Commercial grow-finish swine facilities require a dynamic environment that is able to support raising pigs from 33 kg to market size in the same house. While smaller swine need a higher indoor temperature to maintain their core temperature, larger swine require a lower indoor temperature to prevent heat stress. Most existing mechanically-ventilated swine houses have a ventilation and heating system to control the indoor environment based on the setpoint temperature suggested by industry recommendations. When the indoor temperature is higher than the setpoint, the ventilation will be used to cool down the indoor environment. However, when the outdoor temperature is higher than indoor temperature, the ventilation system will not be able to achieve the lower setpoint temperature. The unachievable setpoint temperature in the cooling season has a significant impact on average daily gain, feed conversion ratio, and welfare of the animals due to heat stress.

In order to reduce heat stress in the cooling season, a misting evaporative system, has been introduced to achieve a lower setpoint temperature. Bridges, Gates, and Turner (1998), who examined the benefits of implementing a misting evaporative system in a natural ventilated swine barn, found a higher average daily gain (ADG) in the swine barn with a cooling system compared to the swine barn without one. By using a thermal-humidity index (THI), Lucas, Randall, and Meneses (2000) showed that the cooling pad with ventilation system is cost-effective in reducing high thermal stressors in the cooling season with low outdoor humidity. Panagakis and Axaopoulus (2006) compared the swine barn THI for three different conditions: cooling pad, misting system, and no cooling system. Their results showed the advantages of having a cooling system over no cooling system, and found that the cooling pad has more advantages than the misting system in terms of water consumption and reduction of apparent heat stress intensity.

Although the advantages of implementing a cooling system in a swine barn are widely known based on the THI evaluation, scant research has focused on the direct economic return in terms of the ADG or FCR that result from implementing a cooling system. Bridges et al. (1998) applied a complex pig growth model (NCPIG) (Bridges, Turner, Stahly, Usry, & Loewer, 1992; Bridges, Turner, Usry, & Nienaber, 1992; Usry, Turner, Bridges, & Nienaber, 1992) and simulated the misting effect to evaluate swine growth performance with natural ventilation system. However, the NCPIG model requires complex parameters input to simulate the swine performance. With the introduction of modern mechanical ventilation and cooling pad systems, a new model approach is needed that requires only a few parameters to simulate pig growth in a mechanical-ventilated swine barn with a cooling pad in order to show how cooling pads affect swine production.

Cooling efficiency is affected by several different factors including pad design, thickness of the pad, water temperature, and air flow rate (Franco, Valera, Madueno, & Peña, 2010). Different cooling pad control offset (difference between indoor and setpoint temperature) have a direct impact on economic returns. A cooling pad tends to reduce efficiency when the inflow airspeed is high, which coincides with higher ventilation stages when the inflow air face velocity is higher. The operation of cooling pads starting at lower ventilation stages have a higher efficiency and may improve the economic return; however, operating cooling pads at lower ventilation stages leads to higher operating frequency as well as higher operation costs. The tradeoff between operating a cooling pad at lower and higher temperature offset requires a comprehensive analysis that directly estimates the economic outcomes for different operations.

To evaluate pig growth performance with and without a cooling pad for a mechanically-ventilated swine barn with different cooling pad control offset, calls for a dynamic model with the capacity to evaluate pig growth performance under different environmental conditions. Chapter 3 of this study modified the simple pig growth model, developed by Moughan et al. (1987), and connects it to a swine housing thermal model to simulate a modern commercialized swine production system without a cooling system, as developed in Chapter 4. The integrated swine production system model (ISPSM) predicts swine growth performance based on the setpoint temperature, indoor temperature, and stage controls with only a few parameters. While the model developed in Chapter 4 does not take into consideration evaporative cooling effects for a swine barn, other research has simulated the cooling effect from the evaporative cooling pad (ECP) based on a constant efficiency (Timmons and Gates, 1988; Timmons and Gates, 1989). Combining the model developed in Chapter 4 with the cooling pad simulation indicates the potential to evaluate economic returns under different cooling pad control offset.

To evaluate the total economic return for use of a cooling pad, swine production costs, including feed cost (*FC*), average energy utility cost (*AEUC*), daily ECP depreciation cost (*DC*) and daily ECP operational cost ($E_{op}C$), were selected and integrated for a simulation to represent the total system cost. Because the length of the growing period is directly related to the grower's profitability, the average daily profit (*ADP,* ADG x revenue per kg pork - overall cost per day) and marginal utility cost (MUC, (AEUC+DC+ $E_{op}C$)/ADG) for the entire growing cycle were considered in order to evaluate the economic return for independent producers and contract producers.

The overall goal of this portion of the study is to evaluate economic returns relative to different cooling pad control offsets. The specific objectives are to 1) adopt the swine production model developed in Chapter 4 with ECP simulations, and 2) based on the proposed simulation and historical weather, evaluate the cooling pad control offsets by *ADG*, *FCR*, AEUC, $E_{op}C$ +*DC*, *MUC*, and *ADP*.

5.2 Materials and Methods

5.2.1 Model overview

A systematic diagram of combining cooling pad simulations and the integrated swine production system model (ISPSM) are shown in Figure 5.1. The ISPSM adopted from Chapter 4 simulates a commercial mechanically-ventilated swine barn with dynamic indoor temperature (°C), ventilation rate (m^3s^{-1}), average energy utility cost for growing cycle (AEUC, \$), average daily gain (ADG, kg), and feed conversion ratio (FCR) based on input parameters such as setpoint temperature, ventilation and heater control stage profiles, feed content, barn thermal resistance, and outdoor temperature. To simulate the cooling pad effect, the outdoor temperature, outdoor humidity, temperature difference between indoor temperatures and the setpoint, and ventilation rate are taken as inputs to calculate the ventilation inlet temperature. The operation cost is then estimated based on the Evaporative Cooling Pad (ECP) operation time. The cooling pads depreciation cost is then calculated based on the total projected cooling pad operation time. All dash blocks in the systematic diagram represent input variables for the analysis. The average daily profit (ADP, \$ d^{-1}) and marginal utility cost estimated from cooling pad depreciation cost (DC, \$ d^{-1}), ECP operational cost ($E_{op}C$, \$ d^{-1}), average energy utility cost (AEUC, \$$kg^{-1}$ d^{-1}), feed conversion ratio (FCR), and average daily gain (ADG, kg) were taken as outputs to calculate further temperature control offset comparisons.

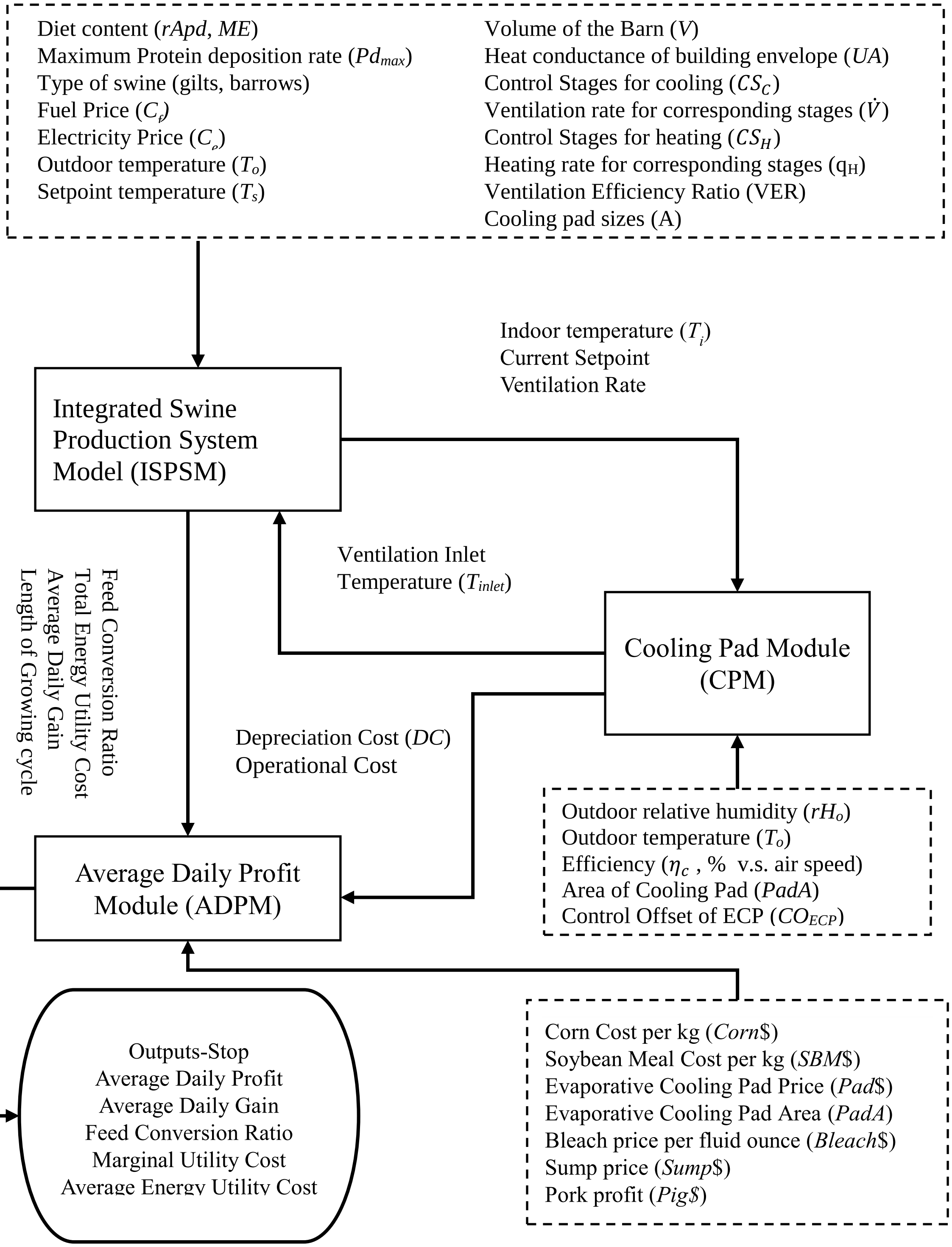


Figure 5.1 The systematic diagram of the Integrated Swine Production System Model (ISPSM) with evaporative cooling pad scheme. The thermal model in ISPSM is modified based on evaporative cooled inlet temperature, which is a function of ventilation air speed, efficiency η_c and outdoor relative humidity, in the Cooling Pad Module (CPM). The depreciation cost and operation cost based on CPM will be further taken as an input for Average Daily Profit Module (ADPM). Based on all parameter related to profit, the ADPM simulate the average daily profit. The output for the entire system scheme includes average daily profit, average daily gain, feed conversion ratio, and marginal utility cost.

5.2.2 Swine barn with evaporative cooling pad simulation and economic evaluation

The current proposal developed a process-based model in Chapter 4 (Integrated Swine Production System Model, ISPSM) to simulate the interaction between swine production performance and swine barn environment for commercial mechanically-ventilated swine barn. The model incorporates empirical equations from literature and modifies a model previously presented by Moughan et al. (1986) to predict both the thermal behavior of the building and swine growth performance. As such, the ISPSM model can be used to evaluate the economic risk associated with environmental control and housing design options.

While the ISPSM has the capability to predict swine performance under different environmental conditions, the model does not consider any cooling system in the system. In order to consider the swine growth performance with operating cooling pad, it is necessary to simulate cooling effects from cooling pads. Previous studies have used a simplified equation to estimate the temperature after evaporative cooling. Cooler temperature passing through a cooling pad can be estimated as shown in Equation 5. 1.

$$T_c = T_o - (T_o - T_w)\eta_c \tag{5.1}$$

where T_c is the temperature after cooling pad, T_o is the dry bulb outdoor temperature, the T_w is the outdoor wet bulb temperature, and the η_c is the cooling pad saturation efficiency. Based on the relationship among wet bulb temperature, dry bulb temperature, and relative humidity (Stull et al, 2011), the wet bulb temperature can be estimated as in Equation 5.2

$$\begin{aligned} T_w = T_o\,\mathrm{atan}[0.151977\,(rH_o + 8.313659)^{0.5}] &+ \mathrm{atan}(T_o + rH_o) \\ &- \mathrm{atan}(rH_o - 1.676331) \\ &+ 0.00391838(rH_o)^{\frac{3}{2}}\,\mathrm{atan}(0.023101\,rH_o) - 4.686035 \end{aligned} \tag{5.2}$$

where rH_o (%) is the outdoor relative humidity.

Inlet temperature after ECP relies not only on outdoor wet/dry bulb temperature, but also cooling efficiency. Most commercial cooling pads have specifications on cooling efficiency curve with regard to different air flow speeds. By incorporating the cooling efficiency based on air flow rate, the cooled inlet temperature can be taken to the swine barn building thermal model in ISPSM. The current research adopts the experiment results from Franco et al. (2010) to estimate the cooling efficiency curve for a Munters 100 mm thick cooling pad as shown in Equation 5.3.

$$\eta_c = 0.699Ve^2 - 7.255Ve + 74.205 \tag{5.3}$$

where Ve is the air speed that passes through the ECP

The cooling pad air flow speed can be estimated based on the ventilation rate and the area of the cooling pad as shown in Equation 5.4.

$$Ve = \frac{\dot{V}}{PadA} \tag{5.4}$$

where $\dot{V}$ ($m^3\ s^{-1}$) is the ventilation rate based on ventilation control stages, and *PadA* is the area of the cooling pads.

ISPSM simulates the indoor temperature based on dynamic heat balance equations as shown in Equation 5.5.

$$\rho_{\bar{a}} C_P V \frac{dT_i}{dt} = (q_p + q_H - q_B - q_F) \tag{5.5}$$

where q_p (W) is the total sensible heat generated by pigs, q_H (W) is the heat generated by fuel heaters, q_B (W) is the heat loss through building envelope, q_F (W) is the heat loss through ventilation fans, t (day) is time, $\rho_{\bar{a}}$ ($kg\ m^{-3}$) is the air density, V (m^3) is the volume of the barn, and C_p ($J\ kg^{-1}\ °C^{-1}$) is the specific heat of the air.

To incorporate the cooled temperature to the building thermal model, q_F calculation is modified from temperature difference between indoor and outdoor temperature to indoor and inlet temperature as follows,

$$q_F = \rho \dot{V} C_P^a (T_i - T_{inlet}) \tag{5.6}$$

where T_{inlet} is the inlet temperature. The T_{inlet} equals to the cooled temperature T_c when the ECP is operating, while T_{inlet} equals to outdoor ambient temperature when the there is no ECP operating. Other details of the swine barn thermal model and pig growth performance can be found in Chapter 4.

The economic returns for swine barns with different operating offset/without ECP are then further evaluated. The current research examines marginal profit that takes into consideration average daily gain, feed conversion ratio, and total utility cost as shown in Equation 5.7.

$$ADP = ADG \times Pig\$ - AEUC - ADG \times FCR \times FC - W_{op} \times E_{op}C - DC \tag{5.7}$$

where ADG ($kg\ day^{-1}$) is the average daily gain, *Pig$* ($\$\ kg^{-1}$) is the pork price, AEUC ($) is the daily average energy utility cost for the growing cycle, FCR is the feed conversion ratio ($kg\ kg^{-1}$), the FC ($) is the feed cost, W_{op}(kg) water loss due to ECP operation includes evaporative and bleed off water, the $E_{op}C$ (\$ kg^{-1}) is the ECP operating cost regards to water and disinfectants cost, and the DC (\$ kg^{-1}) is the depreciation cost for the cooling pad and the sump tank.

The current research assumes sump bleed-off rate is 50% of the evaporative water. The water usage for operation is shown in equation 5.8.

$$W_{op} = 1.5 \times \rho_{\bar{a}} \dot{V} (W_c - W_o) \tag{5.8}$$

$$E_{op}C = WC_{utility} + DisinfecCost_{op}$$

where W_c (kg kg^{-1}) is the indoor humidity ratio after ECP, W_o is the humidity ratio of outdoor temperature, WC is the water cost related to ECP operation, $WC_{utility}$ (\$/m^{-3}) is the utility water rate, $DisinfecCost_{op}$ (\$/m^{-3}) is the disinfectants cost per kg water usage for operation.

By assuming active chlorine concentration maintained at 50 ppm, $DisinfecCost_{op}$ is estimated as shown in equation 5.9 by assuming 5.25% active chlorine concentration for commercially available chlorine laundry bleach.

$$DisinfecCost = \frac{50\,ppm \times 3.3 \times 10^4}{5.25\%} \times Bleach\$ \tag{5.9}$$

where $Bleach\$$ (\$ ounce^{-1}) is the cost for commercially available chlorine laundry bleach.

By assuming ECP operation has 5 years of total expected lifespan of ECP, and straight-line method of depreciation, the daily depreciation of ECP can be estimated as

$$DC = \frac{Pad\$\ \times PadA + sump\$}{5 \times 365} \tag{5.10}$$

where $Pad\$$ is the ECP price, $PadA$ is the ECP area of the barn, and $sump\$$ is the price for sump.

5.2.3 Case study on different cooling pad control offset scenarios

The case study of this model is conducted for a virtual swine barn in Ames, Iowa from 1993 to 2013, because Iowa is one of the major swine production states in the U.S. The city of Ames is in the middle of Iowa and has a comprehensive weather dataset for conducting the case study. The outdoor temperature in Ames is generally higher and the relative humidity fluctuates during the summer as shown in Figure 5.2. The higher outdoor temperature and fluctuating relative humidity have the potential to demonstrate swine barn cooling pad management in the cooling season. Hourly meteorology data were retrieved from the Iowa Environmental Mesonet (IEM) to represent outdoor temperature and outdoor relative humidity. Based on the IEM dataset, 1996 and 1997 are two cool years. In order to discuss the cooling pad effect under high outdoor temperature conditions, the current research does not take 1996 and 1997 into account. All input variables for the integrated swine production system model are listed in Table 5.1. Most of the parameters related to physical system are the same as in Chapter 4.

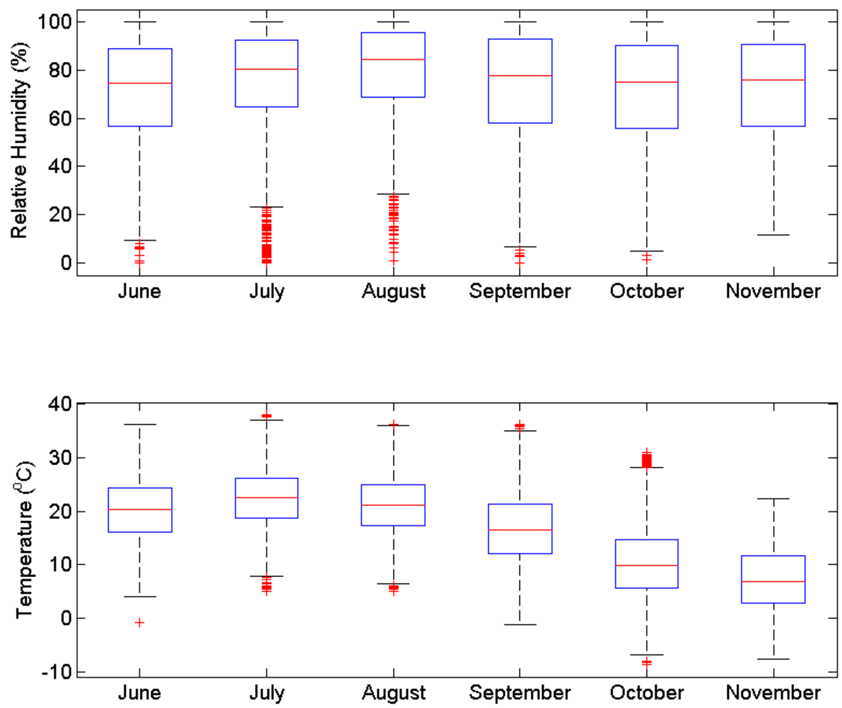


Figure 5.2 Boxplot for outdoor temperature and relative humidity in past 18 years. The central mark indicates the median, the top and bottom edges of the box indicate the 75th and 25th percentiles, the top and bottom mark represents the extreme data points not considered outliers, and the outliers are plotted as '+'.

Table 5.1 Parameters for cooling pad simulation

Parameter	Description	Value	Unit
UA	Heat Conductance for Building Envelope	699.3	W °C^{-1}
APd	Available protein in diet	Same as *control diet* in Table 3.1	NA
$minLP$	Minimum Lipid to Protein Ratio	0.9	NA
MEd	Metabolizable energy in diet	Same as *control diet* in Table 3.1	NA
$Type$	Types of swine: barrows/gilts	Gilts	NA
$\boldsymbol{T_S}$	Setpoint Temperature	Same as Chapter 4 recommendation	°C
$\boldsymbol{T_o}$	Outdoor Temperature	Ames, IA, from June 1, to Oct	°C
$\boldsymbol{rH_o}$	Outdoor relative humidity	Ames, IA, from June 1, to Oct	%
C_e	Electricity Price	0.10	\$ kWh^{-1}
C_f	Fuel Price	0.35	\$ m^{-3}
V	Volume of the Barn	3995	m^3
N	Number of Swine	2400	Head
$\boldsymbol{\dot{V}}$	Ventilation Rate for Corresponding Stages	[9.83 19.83 29.84 51.36 94.40 137.44]	m^3 s^{-1}
$\boldsymbol{CS_V}$	Control Stages for Ventilation	[0 2 4 6 8 10]	°C
$\boldsymbol{VER}$	Ventilation Efficiency Rate	[5.76 7.66 8.29 8.65 8.88 8.97] x 10^{-3}	m^3 s^{-1} W^{-1}
$\boldsymbol{q_{HS}}$	Heating Rate for Corresponding Stages	[0 59 118 177]	kW
$\boldsymbol{CS_H}$	Control Stages for Heating	[0 -2 -4 -6]	°C
$Feed\$$	Corn Cost per kg	0.2038	\$ kg^{-1}
$Pad\$$	Evaporative Cooling Pad Price per m^2	120	\$ m^{-2}
$PadA$	Evaporative Cooling Pad Area	46.45	m^2
$Bleach\$$	Bleach price per fluid ounce	0.1	\$ ounce^{-1}
$Sump\$$	Sump price	1413	\$
$WC_{utility}$	Water cost	3.2	\$ m^{-3}
$Pig\$$	Pig price per kg	1.1	\$ kg^{-1}

Vector type parameters are in bold font

In order to evaluate the economic returns for the cooling pad at different control offsets, scenarios with different control offsets for the cooling pad were designed and compared as shown in Table 5.2. The control offset for the cooling pad is defined by the difference between indoor temperature and the setpoint. If the indoor temperature is higher than the setpoint temperature based on the cooling pad operating offset, the cooling pad will turn on. The current study applied the same ventilation stages as described in Chapter 4, and evaluated different cooling pad operation offsets based on the given ventilation stages. Because the cooling pad is designed not to be operated during minimum ventilation, a scenario with the same setpoint and indoor temperature will not be discussed.

Based on the 18 years' historical weather data, the current research further compared the statistical significance of different objectives, including ADG, FCR, AEUC, MUC, and ADP, on different operating offsets based on Fisher's least significant difference procedure. In order to apply Fisher's least significant difference procedure, data has to be Gaussian distribution. The current research conducted a Kolmogorov-Smirnov test for all datasets to verify the normality for Fisher's least significant difference test.

Table 5.2 Different scenarios for evaporative cooling pad

Scenarios	**Operating Temperature Offset ($T_i - T_{set}$)**	**Unit**
Scenario 1	2	°C
Scenario 2	4	°C
Scenario 3	6	°C
Scenario 4	8	°C
Scenario 5	10	°C
Scenario 6	12	°C
Scenario 7	No cooling pad	No cooling pad

5.3 Results and Discussion

Based on the Kolmogorov-Smirnov normality test, Table 5.3 shows simulation results on the normality test with $\alpha \leq 0.05$. Because in Scenario 7 the ECP operational cost and depreciation cost is not a distribution but a deterministic number (0), the current study did not apply Kolmogorov-Smirnov normality test for the Scenario without a utilizing cooling pad.

Table 5.3 Normality test for different scenario result ($\alpha \leq 0.01$)

	ADG	FCR	AEUC	$E_{Op}C$	MUC	ADP
Scenario1	0	0	0	0	0	0
Scenario 2	0	0	0	0	0	0
Scenario 3	0	0	0	0	0	0
Scenario 4	0	0	0	0	0	0
Scenario 5	0	0	0	0	0	0
Scenario 6	0	0	0	0	0	0
Scenario 7	0	0	0	N/A	0	0

1 indicates that kstest rejects the null hypothesis at the default 5% significance level.
0 indicates that kstest fails to reject the null hypothesis at the default 5% significance level.

Figure 5.3 demonstrates the box plot for the average daily gain (ADG) based on the past 18 years' weather information. The figure shows a trend with a negative relationship between operating offsets and the ADG due to the negative impact of heat stress on the ADG: when the ECP starts to operate at a smaller temperature difference, the cooling system has extra capacity, other than ventilation, to remove heat from the barn. While there is a descending trend on ADG when a cooling pad operates at a higher temperature difference, **no** statistically difference (α = 0.05) was found in any of the smaller offsets of ECP operation. Scenarios 6 and 7 showed a significant difference (p< 0.022) from lower temperature difference Scenarios (Scenario 1-4). Also, the variation of ADG due to outdoor weather condition differences was higher than the variation among different operating temperature offsets. This indicates the limitation of the current cooling facility, which continues to rely strongly on the outdoor temperature and humidity.

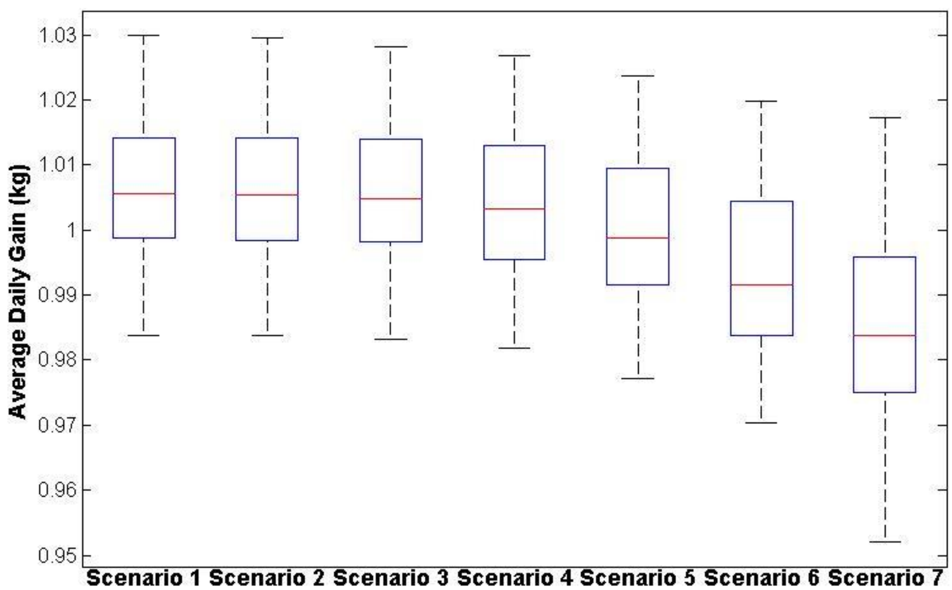


Figure 5.3 Boxplot for average daily gain (ADG) for different scenarios in past 18 years. The central mark indicates the median, the top and bottom edges of the box indicate the 75th and 25th percentiles, the top and bottom mark represents the extreme data points not considered outliers, and the outliers are plotted as '+'.

Figure 5.4 shows the box plot of the feed conversion ratio (FCR) based on past 18 years' weather information. The result shows **no** trend nor statistically significant differences of FCR among different operating offsets. The FCR with regard to different indoor environment temperatures showed no specific trend relative to the outcome. That result is similar to conclusion in Chapter 4 that the FCR in the cooling season is not sensitive for the setpoint temperature. While applying the ECP has a direct effect on decreasing indoor temperature, the decreased indoor temperature has no direct effect on the feed conversion ratio.

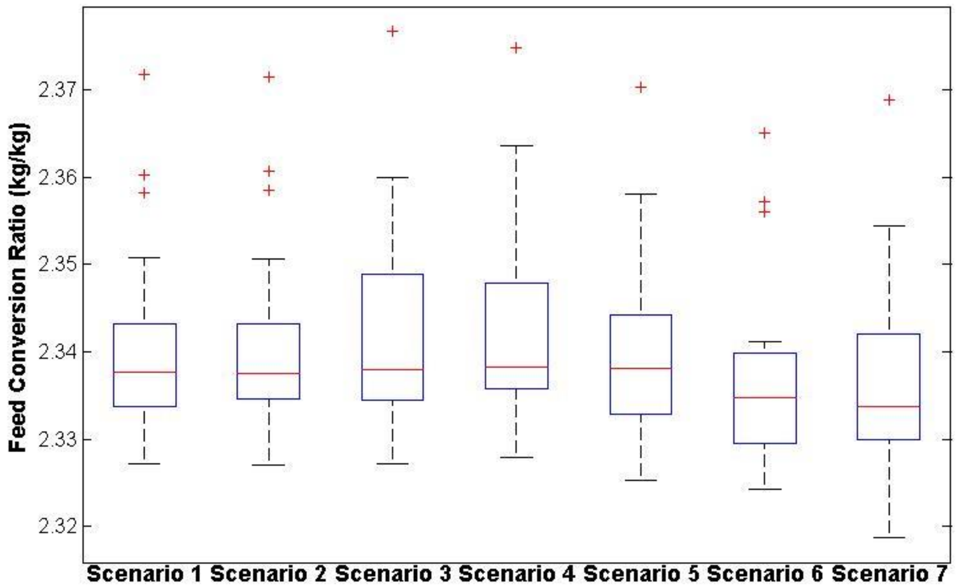


Figure 5.4 Boxplot for feed conversion ratio (FCR) for different scenarios in past 18 years. The central mark indicates the median, the top and bottom edges of the box indicate the 75th and 25th percentiles, the top and bottom mark represents the extreme data points not considered outliers, and the outliers are plotted as '+'.

Figure 5.5 shows the box plot for the average daily electricity and fuel usage (Average Energy Utility Cost, AEUC) based on past 18 years of weather information. The figure shows an increasing trend of AEUC on higher operating offsets. When the ECP operates at a lower offset, the ventilation will tend to operate at a lower stage because of the cooled indoor temperature. Lower stage ventilation rates lead to lower energy requirements, and hence reduce the energy utility cost. The higher offsets and no cooling pad operation (Scenario 6 and 7) showed no statistically significant difference (p-value < 0.012) from lower offsets (Scenario 1-4). This result implies the cooling effect of Scenario 6 was limited and similar to Scenario 7 which did not operate ECP.

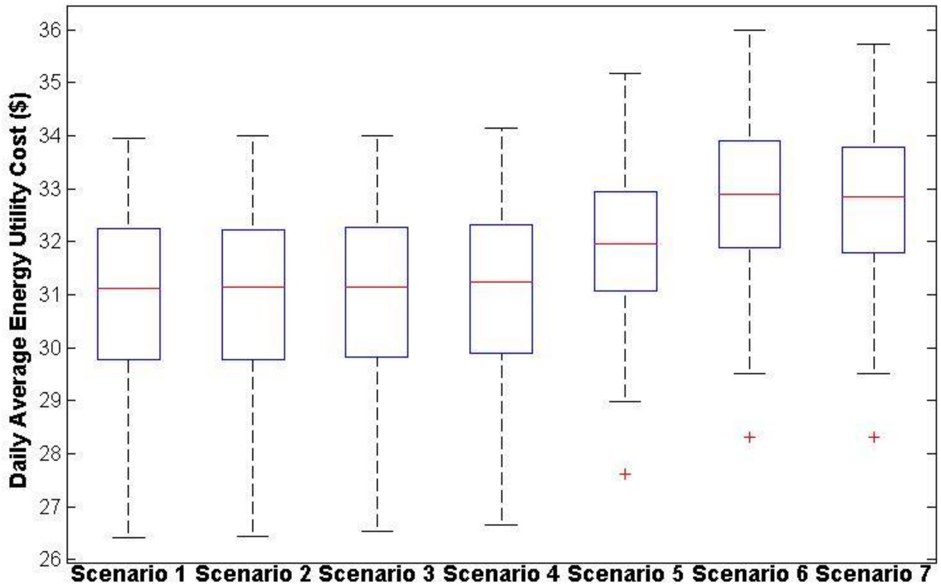


Figure 5.5 Boxplot for Average Energy Utility Cost (AEUC) for different scenarios in past 18 years. The central mark indicates the median, the top and bottom edges of the box indicate the 75th and 25th percentiles, the top and bottom mark represents the extreme data points not considered outliers, and the outliers are plotted as '+'.

Operating the cooling pad at a lower temperature offset led to higher operation costs for water and disinfectants consumption as shown in Figure 5.6. Aside from operation costs, the linear depreciation cost, which relates to the expected time span of the facility, was the major cost. The linear depreciation cost was higher than the operation cost; therefore, the total cost that relates to the cooling pad was driven by depreciation cost. For Scenario 7, the total cost related to ECP was zero because there was no ECP installed and operated. Based on Fisher's least significant test result, there was no statistically significant difference among Scenarios 1, 2, 3. There was also no statistically significant difference found between Scenario 4 and Scenario 3. Scenario 5, 6, 7 were individually statistically significantly different ($\alpha \leq 0.05$) from other scenarios due to less use of ECP. The result indicates a similar ECP-related cost at lower temperature operating offsets.

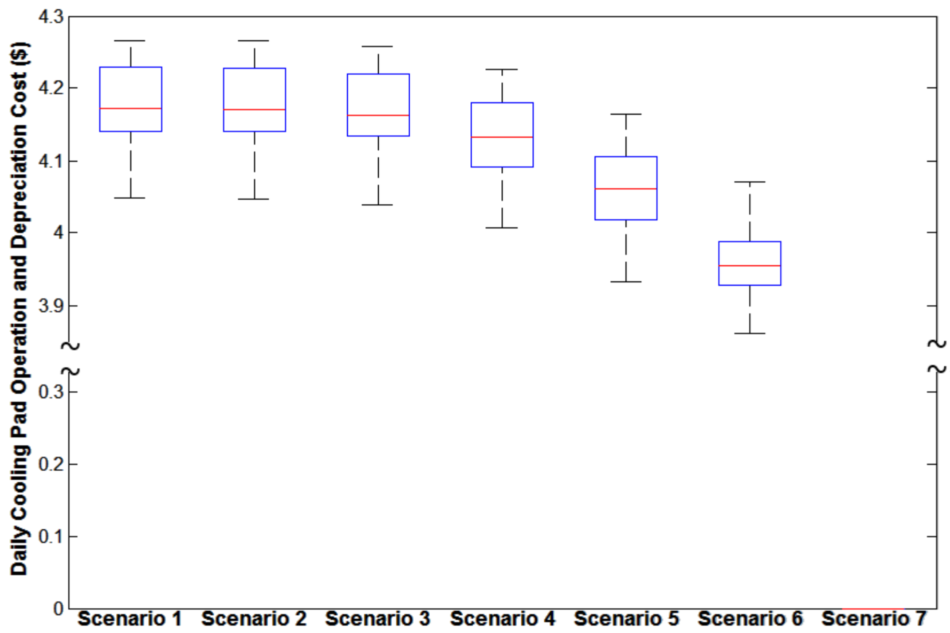


Figure 5.6 Boxplot for daily evaporative cooling pad operation cost ($E_{Op}C$) and depreciation cost (DC) for different scenarios in past 18 years. The central mark indicates the median, the top and bottom edges of the box indicate the 75th and 25th percentiles, the top and bottom mark represents the extreme data points not considered outliers, and the outliers are plotted as '+'.

For contract growers, the daily marginal utility cost (MUC), which is estimated by ECP daily operational cost and average energy utility cost per average daily gain, is shown in Figure 5.7. The MUC tended to be higher at higher ECP temperature control offsets due to the higher AEUC and lower ADG. Scenario 7, on the contrary, had a lower MUC due to no ECP-related costs. The higher ADG and higher AEUC without using ECP in Scenario 7 did not outperform the zero ECP-related cost. There was a statistically significant difference observed between no cooling pad and with cooling pad operation. For contract growers, the result implies that to not operate ECP will result in a significantly lower MUC.

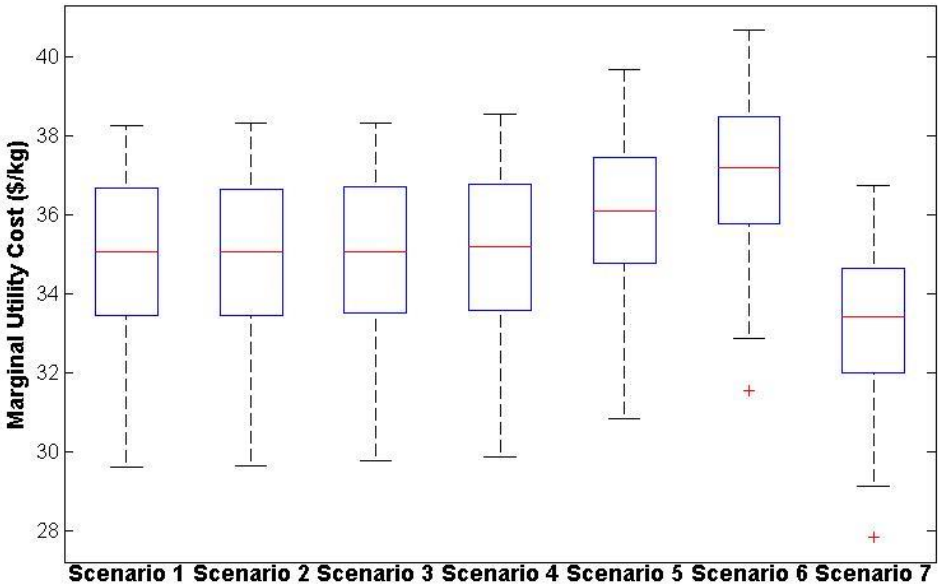


Figure 5.7 Boxplot for daily marginal utility cost (MUC) for different scenarios in past 18 years. The central mark indicates the median, the top and bottom edges of the box indicate the 75th and 25th percentiles, the top and bottom mark represents the extreme data points not considered outliers, and the outliers are plotted as '+'.

Figure 5.8 shows the box plot for average daily profit (ADP) per head based on the past 18 years of weather information. The descending trend from a lower to a higher ECP operating temperature offset indicates the benefit of daily economic return on operating the ECP to reduce heat stress; however, there were **no** statistically significant differences found between scenarios with lower ECP operating temperature offset (Scenarios 1-4). Scenario 6 and Scenario 7 were statistically significantly different from Scenario 1 to Scenario 4 ($p\text{-}value \leq 0.019$), which indicates that operating the ECP at a lower temperature offset had a statistically significant higher ADP compared to no ECP operation or high offset operation. Figure 5.6 also shows a higher deviation of average daily profit when the ECP operated at a higher temperature offset, which suggests that applying the ECP at a lower temperature offset reduced the heat stress risk.

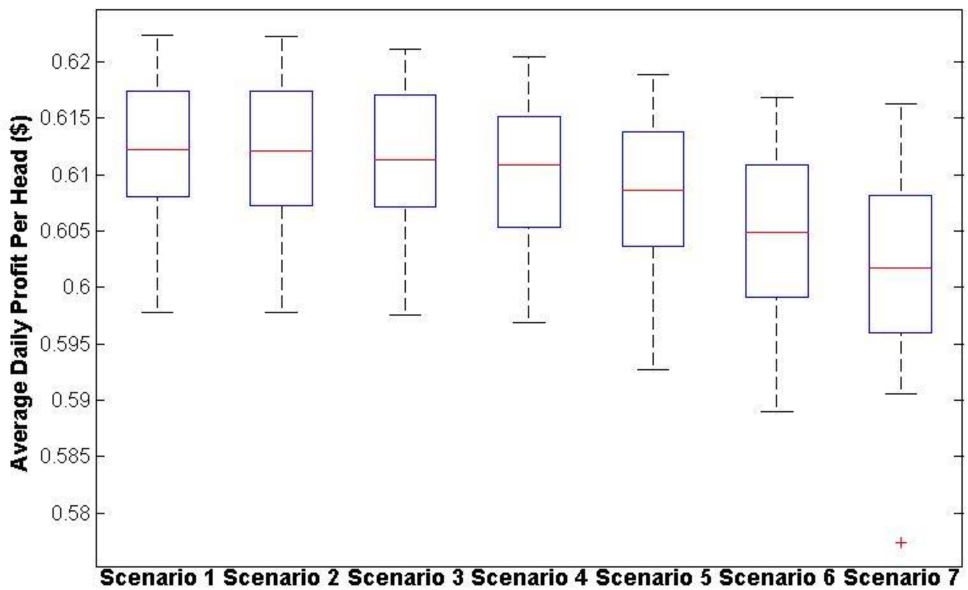


Figure 5.8 Boxplot for average daily profit (ADG) per head of swine for different scenarios in past 18 years. The central mark indicates the median, the top and bottom edges of the box indicate the 75th and 25th percentiles, the top and bottom mark represents the extreme data points not considered outliers, and the outliers are plotted as '+'.

5.4 Conclusion

A simulation-based evaporative cooling pad (ECP) operation offset evaluation was developed to predict the integrated effect of pig growth and swine barn management for a mechanically-ventilated grow-finish swine barn. The simulation-based evaluation incorporated the interaction of swine growth, swine barn, outdoor environment, and ECP operations. Scenarios with different ECP operating temperature offsets were evaluated based on swine production performance indicators such as average daily gain (ADG), feed conversion ratio (FCR), average energy utility cost (AEUC), ECP related operation water cost (WC), marginal utility cost (MUC), and average daily profit (ADP). There was **no** statistically significant difference found for FCR among the different scenarios; however, statistically significant differences of AEUC were found between scenarios with lower ECP operating temperature offsets and higher offsets, in addition to no ECP operation scenarios. This research also found a larger deviation for the ADP when ECP operated at a higher temperature offset and without ECP operation. Simulation results imply the potential benefit of operating ECP at a lower temperature offset to reduce heat stress risk for the ADG and ADP. On the other hand, the simulation results imply that contract growers who focus more on the MUC would choose not to operate a cooling pad under the conditions this chapter discussed. This simulation-based evaluation scheme showed the capacity of investigating the integrated effect based on different scenarios and may be applied to other scenarios for future swine barn evaporative cooling pad management.

CHAPTER 6: OPTIMIZATION OF GROW-FINISH SWINE PRODUCTION BY INDOOR SETPOINT TEMPERATURE CONTROL

6.1 Introduction

Commercial mechanically-ventilated grow-finish swine facilities raise pigs from 30 kg to market size in the same facility, which requires dynamic indoor environment setpoint. To date, temperature control systems have operated on the principle of controlling indoor temperature to a specific setpoint temperature profile. When the indoor temperature is higher than the setpoint, the ventilation and cooling facility will be operated to cool down the indoor environment. When the indoor temperature is lower than the setpoint, the heater will be operated to heat up the indoor environment. The industry recommended setpoint temperature aims to shorten the growing period and is usually assigned by swine live weight without considering the outdoor temperature. This approach works reasonably well when the outdoor temperature is lower than the setpoint temperature. Conversely, when the outdoor temperature is higher than the setpoint temperature, the utility cost to maintain a low setpoint temperature in the cooling season is substantial.

Energy requirements for operating a grow-finish swine barn constitute critical costs for swine producers. Previous studies have shown that ventilation and heating account for 50% of the annual energy usage. Aside from feed, energy utility cost is one of the major costs ($1.2 –$2.6 per 100-kg sold pig) for producers (OMAFRA, 2006; Navia et al., 2007). Therefore, a need exists to minimize the utility cost while maintaining the productivity in terms of the average daily gain and the feed conversion ratio (FCR).

Other than mitigating the energy expense, the average daily gain (ADG) and feed intake are also high relative to the indoor growing environment. Both average daily gain (ADG) and feed intake are observed to be lower during the summer season (Heitman and Huges, 1949; Morrison, 1966; Hale et al. 1968; Hahn et al., 1987; Lopez et al., 1991; Christon, 1998; Myer et al., 1998; Myer et al., 2008; White et al., 2008; Lewis and Bunter, 2011; Renaudeau et al., 2014) By controlling the setpoint temperature to affect the indoor environment, there are potentials to manage ADG and feed intake based on environment control. Moreover, adjustments in the setpoint have the potential to reduce ventilation and heating energy requirements while not affecting the FCR as described in Chapter 4.

To adjust the setpoint temperature, understanding the swine-environment interaction is important. The relationships among air temperature, efficiency of swine live weight gain, nutrient intake, and heat production have been quantified by a number of researchers (Black et al., 1987; Bridges, Turner, Stahly, Usry, & Loewer, 1992; Bridges, Turner, Usry, & Nienaber, 1992; Usry, Turner, Bridges, & Nienaber, 1992). Bridges et al. (1998) evaluated the economic feasibility of a cooling system by implementing the NCPIG model in a natural ventilation system based on swine performance. Chapter 4 developed a process-based model (ISPSM, integrated swine production system model) and tested the sensitivity of the interaction between the swine barn management and the swine production performance for mechanically-ventilated commercial grow-finish swine barns. The sensitivity results showed the potential to control swine production performance by controlling setpoint temperatures. Although these models report the important relationship between indoor environments and swine production performance, these studies made **no** attempt to optimize the indoor setpoint temperature for swine housing.

While the setpoint temperature optimization approach has not yet been widely implemented as a tool to evaluate economic return in the swine industry, other agriculture production systems have utilized the optimization approach to maximize economic return with different outdoor environment and production practices. Timmons and Gates (1986) used an optimization approach to maximize daily marginal profits based on setpoint temperature for broiler housing. Seginer, Shina, Albright, and Marsh (1991) optimized the setpoint temperature for total profit over the entire growing cycle of a greenhouse production system by assuming future weather events and projected growing periods. Both studies demonstrated potential economic savings based on their optimization approach for different production systems.

An optimum setpoint control has shown to be beneficial to economic returns in the agriculture industry; however, the swine housing setpoint temperature optimization has received scant attention because of the complex swine-environment interaction. Based on recent research on the swine-environment interaction, combining the swine production model and a setpoint temperature optimization procedure provides important insights for swine producers.

Producers have different objectives in terms of their economic return. Integrated producers, who pay more attention to feed costs, are assumed to be more interested in optimizing the feed conversion ratio (FCR). Contract producers, who have their swine feed provided by integrators, are assumed to be more focused on minimizing the marginal utility cost (MUC, utility cost per weight gain). Independent growers, who focus on total economic returns (DP, daily profit), need to address average daily gain, utilities, and feed cost. While different producers have their own practices to maintain profitability, there is no consistent strategy to address the relationships between the setpoint temperature and outdoor environment. Therefore, a need exists to develop a computational optimum control capacity to maximize and discuss the profitability for different producers in different seasons.

The overall goal of this research is to investigate the optimized indoor setpoint temperature for different perspectives and the tradeoff between different objectives. The specific objective is to develop an economic optimization procedure to determine a dynamic indoor setpoint temperature to optimize three different objectives (feed conversion ratio, FCR; marginal utility cost, MUC; Daily Profit, DP) as a function of (a) electricity and fuel cost, (b) cost related to evaporative cooling pad (ECP) (b) house thermal characteristics (UA value), (c) forecast and observed outdoor air temperature and relative humidity, (d) current pig live weight and its heat gain, and (e) swine production management.

6.2 Materials and Methods

6.2.1 Daily setpoint temperature optimization procedure

To optimize the economic return for swine producers, objective functions were defined to present different perspectives. For integrated producers, the optimization scheme aimed to minimize the feed conversion ratio (FCR) for next day. For contractors, the current research aimed to minimize the next day's utility cost per weight gain (MUC, marginal utility cost). This marginal utility cost is also related to average daily gain, which is one of the major factors for contractors' profitability based on facility stocking rate. For independent producers, the current research aimed to optimize the daily profit for next day. The current research defined profit based on only pork price per live weight, feed cost, energy utility cost, and ECP operation cost. Other costs were not considered in the scope of the current research. To compare the optimization results, the economic performance of entire growing cycle between the recommended and optimum setpoint temperature were conducted. The basis for optimizing the 2400-head grow-finish production process for a mechanical-ventilated double-wide swine barn was the model developed and described in Chapter 4 and Chapter 5.

The system diagram for optimization procedure is shown in Figure 6.1. At day D, the ISPSM model estimated the objectives for future day D+1 based on forecasted weather with different setpoint temperatures. The system then used the optimum setpoint temperature as the setpoint temperature for D+1. The *current* swine production status was further *updated* based on the optimized setpoint temperature and historical outdoor temperature to represent *real* value.

To ensure that the indoor temperature did not overwhelm the thermoneutral zone, the current research restricted the indoor setpoint temperature search domain from 2^oC lower than low critical temperature (LCT) to 2^oC higher than high critical temperature (HCT) based on the literature (Christianson et al., 1982; NRC, 2012). The current research used LCT from NRC (2012) because of the limitation for ISPSM, which adopted LCT equations from NRC (2012). HCT from Christianson et al. (1982) was applied to simulate the upper bound for swine barn setpoint, which was higher than thermoneutral zone recommended in NRC (2012).

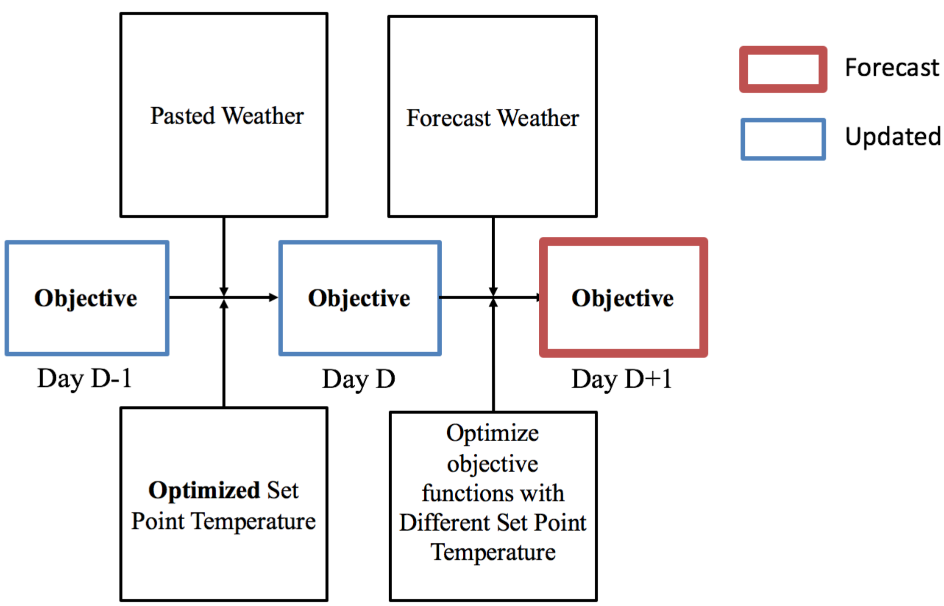


Figure 6.1. Optimization and update procedure for the optimum setpoint temperature selection. At day D, ISPSM estimates the objectives for future day D+1 based on forecasted weather with different setpoint temperature. The system then uses the optimum setpoint temperature as the setpoint temperature for D+1. The *current* swine production status is further *updated* based on optimized setpoint temperature and historical outdoor temperature to represent *real* value.

The optimization procedure was based on the following functions by using the ISPSM model to quantify the variables associated with production:

For integrated producers:

$$\min \hat{Z}^{D+1} = \widehat{FCR}^{D+1} = \frac{\widehat{FI}^{D+1}}{\widehat{W}^{D+1} - W^{D}} \tag{6.1}$$

For contract producers:

$$\min \hat{Z}^{D+1} = \widehat{MUC}^{D+1} = \frac{\hat{C}_{ele}^{D+1} + \hat{C}_{fuel}^{D+1} + \widehat{ECP\$}^{D+1}}{\widehat{W}^{D+1} - W^{D}} \tag{6.2}$$

For independent producers:

$$\begin{aligned} \max \hat{Z}^{D+1} &= \widehat{DP}^{D+1} \\ &= \left(\widehat{W}^{D+1} - W^{D}\right)Pig\$ - \left(\hat{C}_{ele}^{D+1} + \hat{C}_{fuel}^{D+1} + \widehat{ECP\$}^{D+1}\right) - \widehat{FI}^{D+1} \times FC \end{aligned} \tag{6.3}$$

With constraints to integrated swine production model (ISPSM)

$$s.t.\ \left(\widehat{FI}^{D+1}, \hat{C}_{ele}^{D+1}, \hat{C}_{fuel}^{D+1}, \widehat{W}^{D+1}, \widehat{ECP\$}^{D+1}\right) = \boldsymbol{f_{ISPSM}}(W^{D}, \hat{T}_{o}^{D+1}, \widehat{rH}\,_{o}^{D+1}, \boldsymbol{T_{set}^{D+1}}) \tag{6.4}$$

$$LCT \le \boldsymbol{T_{set}^{D+1}} \le UCT$$

$$\bar{T}_{set}^{D+1} = arg\,min\,\hat{Z}^{D+1}$$

where

$\hat{Z}^{D+1}$ denotes the predicted objective at time D+1

$\widehat{FCR}^{D+1}$ denotes the predicted marginal utility cost (FCR) at time D+1

$\widehat{MUC}^{D+1}$ denotes the predicted marginal utility cost (MUC) at time D+1

$\widehat{DP}^{D+1}$ denotes the predicted daily profit at time D+1

$\widehat{FI}^{D+1}$ denotes the predicted feed intake at time D+1

$\widehat{W}^{D+1}$ denotes the predicted live weight for one pig at time D+1

W^{D} denotes the real live weight for one pig at time D

$\hat{C}_{ele}^{D+1}$ denotes the predicted electricity cost at time D+1

$\hat{C}_{fuel}^{D+1}$ denotes the predicted fuel cost at time D+1

$\widehat{ECP\$}^{D+1}$ denotes the predicted evaporative cooling pad related cost

$Pig\$$ denotes the revenue for pig live weight per kg

FC denotes the feed cost

$\boldsymbol{f_{Y}}$ denotes integrated swine production model (ISPSM) developed in Chapter 4 and 5

$\hat{T}_{o}^{D+1}$ denotes forecasted outdoor temperature at time D+1

$\widehat{rH}_{o}^{D+1}$ denotes forecasted outdoor relative humidity at time D+1

T_{set}^{D+1} denotes the setpoint temperature at time D+1, also is the solution domain

$\bar{T}_{set}^{D+1}$ denotes the optimum setpoint temperature at time D+1

The *real* objective outcomes and pig live weight are updated by the optimum setpoint temperature and historical outdoor temperature.

$$\left(FI^{D+1}, C_{ele}^{D+1}, C_{fuel}^{\square+1}, W^{D+1}, ECP\$^{D+1}\right) = \boldsymbol{f_Y}(W^{D}, T_o^{D+1}, rH_o^{D+1}, \bar{T}_{set}^{D+1}) \quad (6.5)$$

where

FI^{D+1} denotes the real feed intake at time D+1

C_{ele}^{D+1} denotes the real electricity cost at time D+1

C_{fuel}^{D+1} denotes the real fuel cost at time D+1

W^{D+1} denotes the real pig live weight at time D+1

W^{D} denotes the real live weight for one pig at time D

T_o^{D+1} denotes the outdoor temperature at time D+1

rH_o^{D+1} denotes the outdoor temperature at time D+1

$\bar{T}_{set}^{D+1}$ denotes the optimum setpoint temperature at time D+1

$ECP\$^{D+1}$ denotes the evaporative cooling pad relative cost at time D+1

Because the optimization problem proposed by the current research was a highly-nonlinear problem, the current research optimized the optimum setpoint by searching all the solution domains from LCT to UCT with 0.5°C incremental intervals.

6.2.2 Location and model input

Ames, Iowa was chosen for a case study because it is one of the major swine production regions in the United States. It also has comprehensive weather data information to evaluate the model performance. Weather information in 2013 was chosen to conduct the case study due to the high ambient temperature in summer and low ambient temperature in spring (Fig 6.2). This weather pattern provides a valuable platform to demonstrate the optimum setpoint differences between summer and winter season.

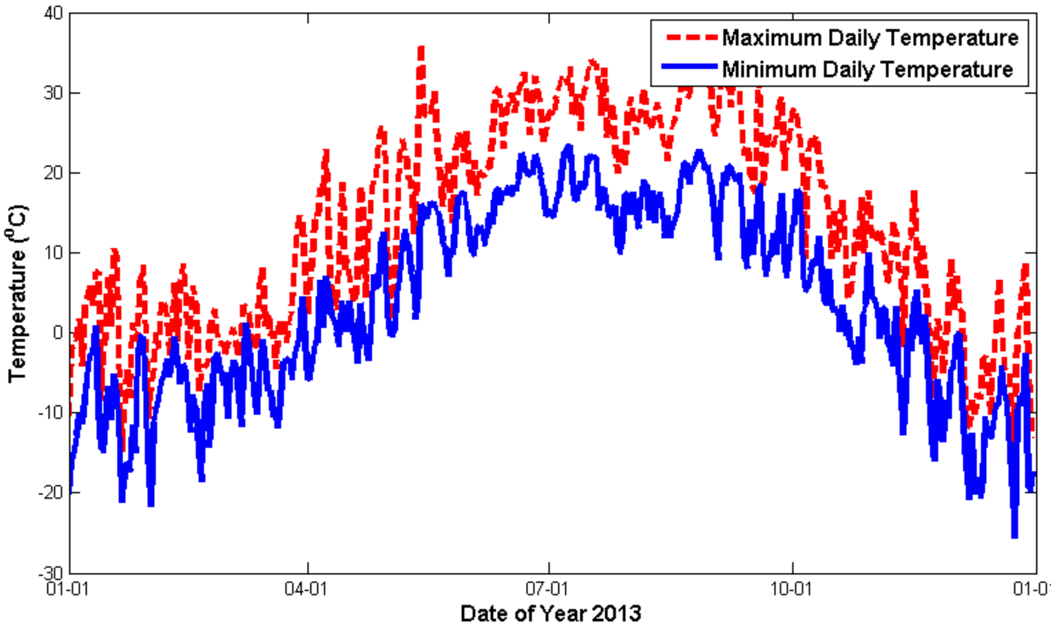


Figure 6.2 Maximum and minimum daily outdoor temperature of Ames, Iowa in 2013. The red dashed line is the maximum daily temperature, and the blue solid line is the minimum daily temperature

The number of 2400 head of gilts in a mechanically-ventilated grow-finish double-wide swine barn for the proposed case study was based on the design obtained from Chapter 4 and Chapter 5. Hourly meteorology data was retrieved from the Iowa Environmental Mesonet (IEM) to represent the real-time and historical outdoor environment. Weather information in 2013 was taken as the real-time weather in the case study while the average historical weather information (1990 - 2012) was considered as the forecasted weather in the optimization procedure.

Two sets of scenarios were designed to raise the gilts from 33 kg to 130 kg in (1) the heating season (from Jan 1st to Mar) and (2) the cooling season (from June 1st to Oct). The comparisons among different optimum and industry-recommended setpoint indoor temperatures for both seasons were conducted. All parameters for optimization procedures are listed in Table 6.1.

Table 6.1 Parameter for optimization process

Parameter	Description	Value	Unit
UA	Heat Conductance for Building Envelope	699.3	W °C^{-1}
APd	Available Protein in Diet	*Control Diet* in Table 3.1	g kg^{-1}
$minLP$	Minimum Lipid to Protein Ratio	0.9	*NA*
MEd	Metabolizable Energy in Diet	*Control Diet* in Table 3.1	kJ
C_e	Electricity Price	0.10	\$ kWh^{-1}
C_f	Fuel Price	0.35	\$ m^{-3}
rPd_{max}	Ratio to Reference Maximum Daily Protein Deposition Rate	1	NA
$Type$	Types of swine: barrows/gilts	Gilts	NA
$\boldsymbol{T_o}$	Outdoor Temperature	Heating Scenario: from Jan. 1, 2013 to Mar. 2013 Cooling Scenario: from May 1, 2013 to Oct. 2013	°C
$\boldsymbol{rH_o}$	Outdoor relative humidity	Heating Scenario: from Jan. 1, 2013 to Mar. 2013 Cooling Scenario: from May 1, 2013 to Oct. 2013	NA
V	Volume of the Barn	3995	m^3
N	Number of Swine	2400	Head
$\boldsymbol{\dot{V}}$	Ventilation Rate for Corresponding Stages	[9.83 19.83 29.84 51.36 94.40 137.44]	m^3 s^{-1}
$\boldsymbol{CS_v}$	Control Stages for Ventilation	[0 2 4 6 8 10]	°C
$\boldsymbol{VER}$	Ventilation Efficiency Rate	[5.76 7.66 8.29 8.65 8.88 8.97] x 10^{-3}	m^3 s^{-1} W^{-1}
$\boldsymbol{CS_{ECP}}$	Control offset for ECP	2	°C
$\boldsymbol{q_{HS}}$	Heating Rate for Corresponding Stages	[0 59 118 177]	kW
$\boldsymbol{CS_H}$	Control Stages for Heating	[0 -2 -4 -6]	°C
$Feed\$$	Corn Cost per kg	0.2038	\$ kg^{-1}
$E_{op}C$	ECP operation Cost Per Volume Water Usage	6.47	\$ m^{-3}
DC	Depreciation Cost for ECP	3.83	\$ d^{-1}
$Pig\$$	Pig price per kg	1.1	\$ kg^{-1}

Vector type parameters are in bold font

6.3 Results and Discussion

Based on the optimization procedure of a commercial mechanically-ventilated swine house designed in Ames, Iowa, production performance indicators (Average Daily Gain, ADG; feed conversion ratio, FCR; Marginal Utility Cost, MUC; Total Utility Cost per pig, TUC; daily profit, DP) in both cooling (with or w/o ECP) and heating seasons are presented in Table 6.2

Table 6.2 Comparison among difference scenarios. Results from different objective function is shown with brackets

		ADG (kg/day)	Utility Cost per Pig ($/head)	MUC per ADG ($/kg)	FCR (kg Feed/kg Gain)	Profit per Pig ($/head - day)
Heating Season	Optimized	1.10 (FCR) 1.10 (DP) 1.09 (MUC)	1.20(FCR) 0.96(DP) 0.81(MUC)	29.46(FCR) 23.45(DP) 19.94(MUC)	2.448(FCR) 2.459(DP) 2.467(MUC)	0.653(FCR) 0.654(DP) 0.650(MUC)
	Industry	1.10	0.89	21.75	2.47	0.653
Cooling Season	Optimized w ECP	1.01 (FCR) 1.01 (DP) 0.86 (MUC)	1.63(FCR) 1.63(DP) 0.92 (MUC)	40.36(FCR) 40.36(DP) 22.65(MUC)	2.34(FCR) 2.34(DP) 2.37(MUC)	0.619(FCR) 0.620(DP) 0.527(MUC)
	Industry w ECP	0.99	1.44	35.64	2.34	0.610
	Optimized w/o ECP	0.99 (FCR) 0.99 (DP) 0.85 (MUC)	1.55(FCR) 1.54(DP) 0.84(MUC)	38.30(FCR) 38.02(DP) 20.63(MUC)	2.34(FCR) 2.34(DP) 2.39(MUC)	0.608(FCR) 0.608(DP) 0.518(MUC)
	Industry w/o ECP	0.97	1.36	33.70	2.33	0.599

In the heating season, all scenarios (optimum and industry setpoint temperature) have similar ADG and profit. The optimum MUC minimizes the future day marginal utility cost, and it also had the lowest overall MUC. Optimum setpoint temperatures for FCR had the lowest FCR compared to other scenarios, which is consistent with results shown in Chapter 4 that FCR is sensitive to setpoint during the heating season.

In the cooling season, a system with setpoints designed for the optimum FCR and DP tended to have similar average daily gain; however, a system with setpoints designed for the optimum MUC tended to have a smaller ADG compared to other objectives. For utility cost per pig, while a system optimized for FCR and DP showed higher cost than the industry scenario, a system optimized for MUC showed the lowest cost. Due to the objective function of the optimum MUC scenario, the optimum setpoints that aimed for minimizing MUC tended to minimize the daily utility cost per daily growth over the entire growing cycle. The result of the optimum MUC scenario showed a higher FCR compared to the two other scenarios in the cooling season. Lower ADG and higher FCR also led to a lower profit by optimizing the MUC system in the cooling season. The system with ECP had a generally higher ADG due to its extra cooling capacity and higher utility cost because of extra costs from the cooling pad operations and depreciation.

While the results for different optimization scenarios and corresponding swine production performance indicators showed the potential of the optimization process to reduce cost/increase revenue for producers, those results did not demonstrate the reasons for those outcomes. To better discuss the potential reasons for the final optimized results, the optimized setpoint temperature profiles and corresponding swine growth curves were further investigated.

In the heating season, the swine growth curves for the industrial recommended setpoint temperatures and all scenarios were similar for all objective functions as shown in Figure 6.3.a. Most of the optimized setpoint temperature was lower than the industry recommendation as shown in Figure 6.3.b. The optimization process kept the setpoint temperature closer to NRC recommended LCT, which is lower than the industry recommendation in order to achieve two benefits: 1) The swine have the best growth performance in terms of ADG based on the ISPSM model. 2) The energy requirements for heating were less than the industrial setpoint temperature due to the lower LCT when the pigs are small and the outdoor temperature is low.

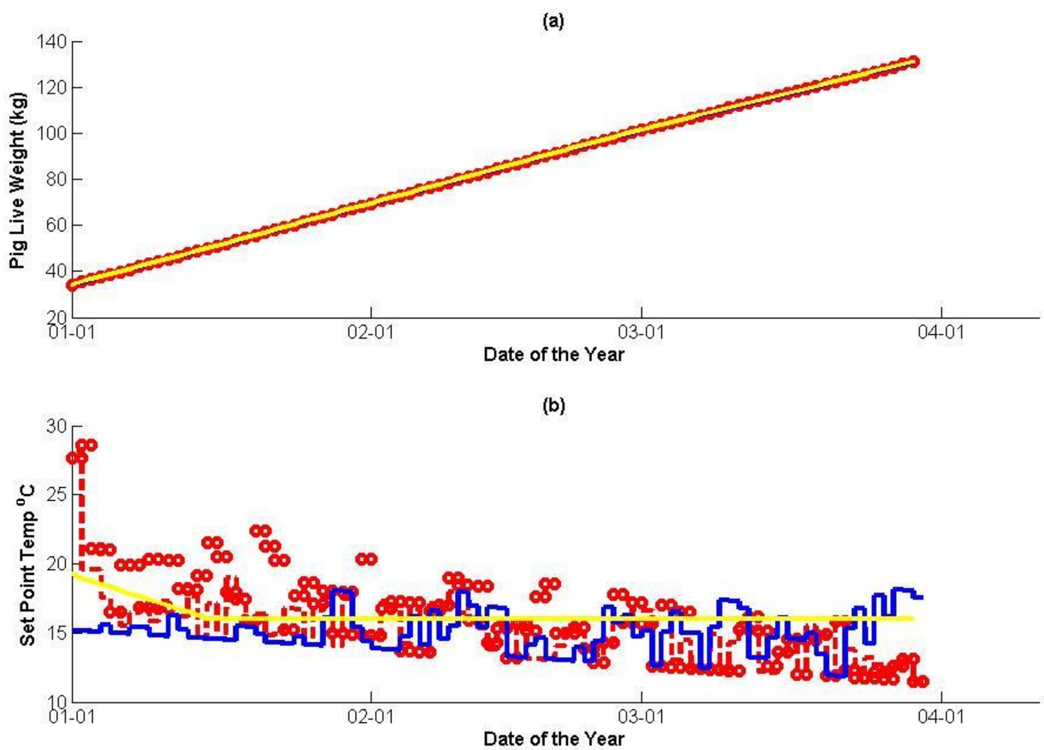


Figure 6.3 (a) pig growth curve for different objective functions in the heating season, and (b) the setpoint temperature profile for different objective function in the heating season. Red circle presents result for optimum FCR. Red dash line presents result for optimum average daily profit (ADG). Blue line presents result for optimum marginal utility cost (MUC). Yellow line presents the industrial recommendations.

In the heating season, the setpoint temperature profile for the optimum FCR scenario was shown to be the highest among all the scenarios (Figure 6.3.b). The higher indoor setpoint temperature compared to the LCT tended to perform a better FCR in the heating season, which is consistent with the results from Chapter 4. A better FCR may outperform the ADG with regard to daily profit. For the maximum daily profit (DP), this effect led to a setpoint temperature profile between the optimum MUC and FCR setpoints.

However, in the later stage of the grow-finish pigs, the optimized setpoint temperature for the minimum MUC was higher than the industrial recommendation, optimum FCR, and DP setpoint profiles. When the swine heat production increases due to higher live weight and the outdoor temperature increases, producers use ventilation fans to maintain the setpoint temperature. While the industry recommended setpoint temperature suggests a low setpoint that requires high electricity costs, the optimum MUC setpoint profile requires less electricity expense and further saves on utility costs.

Based on the assumption of the objective functions, contract producers, who aim for a lower MUC, will have a different strategy than integrated producers and independent producers during cooling season, who focus more on FCR and DP independently. The optimum setpoint temperatures for independent producers and integrated producers were shown to have a similar trend with the Prairie Swine Centre recommendation. Optimum practice for contract producers, on the contrary, have an opposite strategy that is designed for a lower setpoint when the outdoor temperature is low and a higher setpoint when the outdoor temperature is high.

In the cooling season, the pig growth curves regard to the optimum FCR, DP, and Industry setpoint profiles were similar as shown in Figure 6.4. The scenario for the optimum MUC demonstrated a slower pig growth curve compared to other setpoint scenarios due to the higher setpoint profiles as shown in Figure 6.5. Pig growth curves for with/without ECP operation showed similar patterns among all scenarios. These results imply that the setpoint operation strategy should be consistent between with and without ECP operation. A system with ECP has a two to three days shorter growing cycle as shown in Figure 6.4.b due to the extra cooling facility and lower setpoint temperature (Figure 6.5).

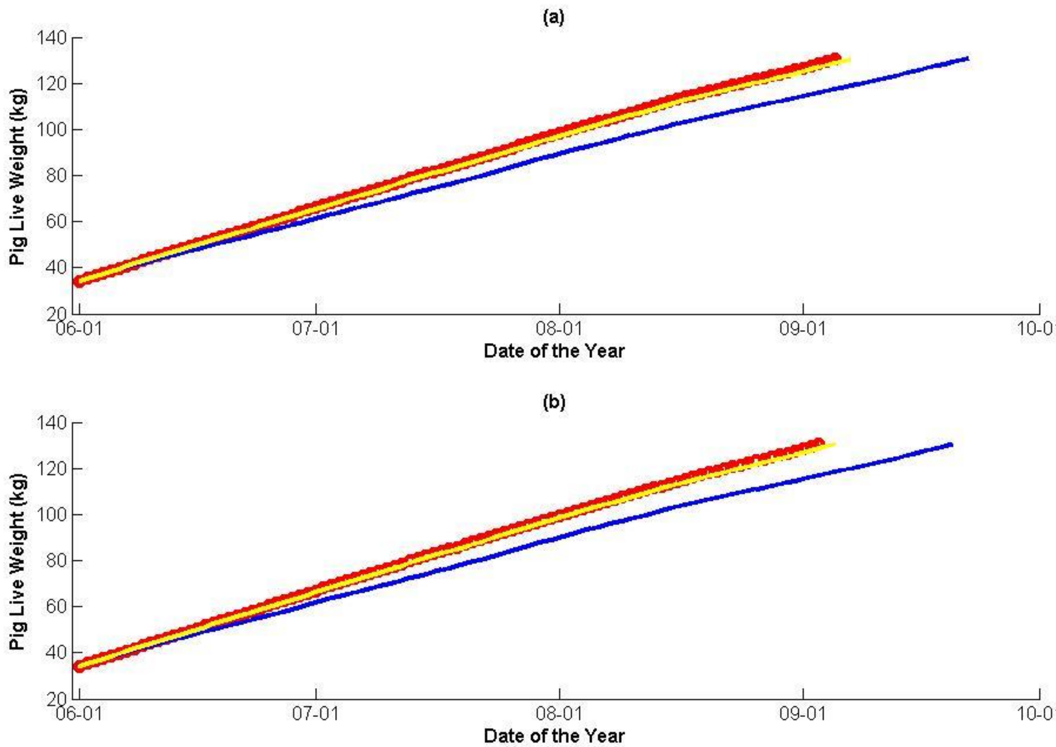


Figure 6.4 pig growth curve for different objective functions in the cooling season (a) without evaporative cooling pad operation and (b) with evaporative cooling pad operation. Red circle presents result for optimum FCR. Red dash line presents result for optimum average daily profit (ADG). Blue line presents result for optimum marginal utility cost (MUC). Yellow line presents the industrial recommendations.

While the optimum DP, FCR and industrial setpoint scenarios try to maintain the optimum growth environment for the swine in the cooling season, it is not economically feasible for contract growers to maintain the setpoint with a high outdoor temperature profile. To reduce the MUC, the optimum setpoint temperature designed for contract growers tended to be higher than the industry recommendation to meet the outdoor temperature as shown in Figure 6.3. A smaller difference between the indoor and setpoint temperatures caused a lower ventilation-related energy expense. Although the optimum MUC had the lowest utility cost for the entire growing cycle in the cooling season, the length of the growing cycle increased.

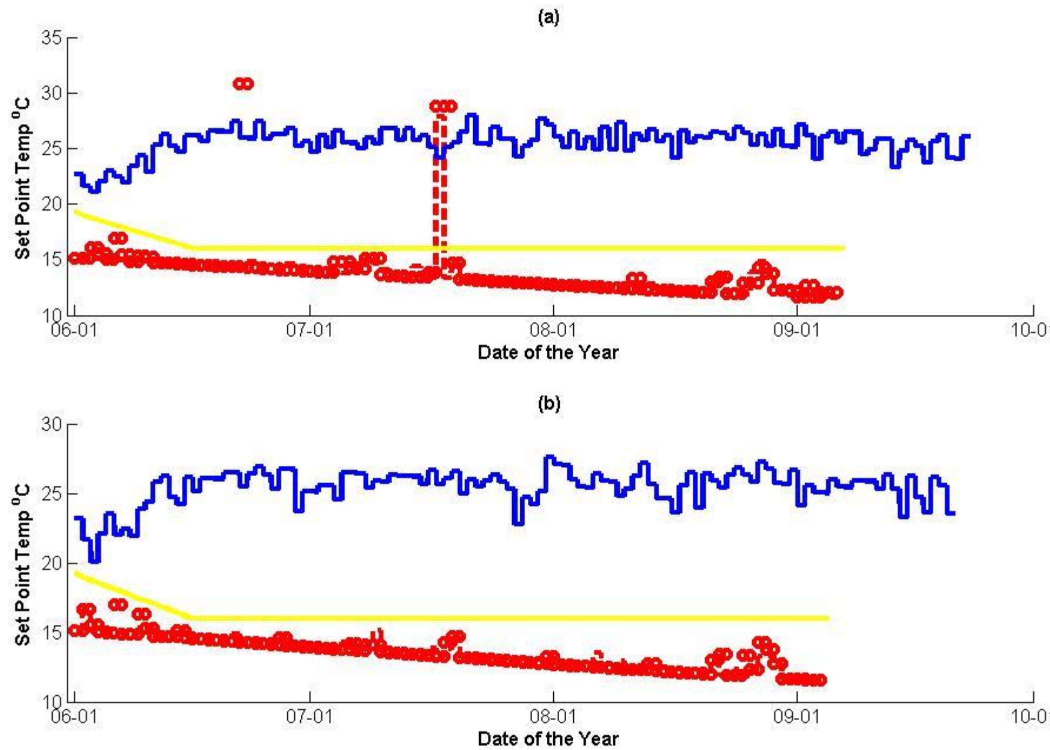


Figure 6.5 The setpoint temperature profile for different objective functions in the cooling season (a) without evaporative cooling pad operation and (b) with evaporative cooling pad operation. Red circle presents result for optimum FCR. Red dash line presents result for optimum average daily profit (ADG). Blue line presents result for optimum marginal utility cost (MUC). Yellow line presents the industrial recommendations.

In Figure 6.5, the high setpoint for the optimum MUC scenario had the potential to increase heat stress and increase FCR as shown in Table 6.2. Because of the larger setpoint temperature range compared to the scenario in Chapter 4, the result was **not** consistent with the trend discussed in Chapter 4 that described the temperature setpoint as being not influential to the FCR performance. A moderate setpoint profile between the optimum MUC and FCR scenarios, however, has a potential to decrease utility costs in the cooling season while maintaining the FCR at the similar range.

In the cooling season, scenarios with the ECP for the optimum FCR and DP tended to have lower setpoint profiles than scenarios without ECP as shown in Figure 6.5. Due to the extra cooling capacity from ECP, scenarios with the ECP had a greater chance to meet the LCT recommended by the NRC (2012) to achieve a better performance. This result also demonstrates the importance of implementing ECP to maintain the indoor environment closer to LCT.

Based on the assumption of the objective function, results imply that contract producers had a conflicting strategy from integrated and independent producers in the cooling season. Contract producers tended to choose high setpoint temperature to reduce utility costs, but integrated as well as independent producers tended to choose low setpoint temperature to reduce the heat stress. Industry recommendations from Prairie Swine Centre (2000) suggested setpoint temperatures in between the two different preferences. The result implies a compensation between different optimum practices was chosen based on the experience.

6.4 Conclusion

A process model-based indoor setpoint optimization procedure was developed to optimize the entire growing cycle of swine production performance for a commercial mechanically-ventilated grow-finish double-wide swine barn. The proposed procedure defined different objective functions to represent different perspectives in the industry: 1) minimize the feed conversion ratio (FCR) for integrated producers, 2) minimize the marginal utility cost (MUC) for contract growers, and 3) maximize the daily profit (DP) for integrated producers. A simulation was conducted in Ames, Iowa, with different objectives to evaluate the optimization procedure. The results showed a higher setpoint temperature during the cooling season and a longer growing period with regard to minimizing the marginal utility cost for contractors. In order to produce income, Integrators and independent producers tend to meet the setpoint with a lower temperature to create the best feed conversion ratio and maximum average daily gain. While the optimized setpoint temperature profiles are similar for both with or without an evaporative cooling pad (ECP) operation, the setpoint tends to be higher for scenarios without ECP due to the difficulties to achieve LCT. While contract producers and independent/ integrated producers have different optimum setpoint temperature profiles, a setpoint temperature profile in between has the potential to reduce the MUC while keeping the FCR low. The economic benefits from incorporating the optimization procedure demonstrates the potential for future swine housing operation and design.

CHAPTER 7: SUMMARY AND RECOMMENDATIONS

7.1 Summary

This study addressed several activities in grow-finish swine barn operations. It includes a swine growth model development and evaluation for modern grow-finish swine performance (Chapter 3), a swine barn – swine growth system model with a sensitivity analysis of swine barn management and potential influence on swine growth (Chapter 4), an application of the dynamic system model to suggest cooling pad operation offset (Chapter 5), and an optimum real-time setpoint temperature suggestion based on the proposed dynamic model (Chapter 6).

First, an existing simplified model was modified to present swine performance under different indoor temperatures as a modified simple pig growth model (MSPGM) in order to evaluate more recent swine growth performance. Parameters from recent publications were applied to update the swine nutrient partitioning scheme. The model was further calibrated and validated based on two individual swine growth cycles with the same swine breeding line held in 2016 to represent more recent swine growth performance. The calibrated parameters showed a 10% leaner minimum body lipid to protein ratio than that reported by De Lange et al. (1995), 7% more feed consumption than that from Schinckel et al (2012), a 27% higher potential to deposit protein compared to Black et al. (1987), 10% lower in energy requirements for depositing body lipid compared to Tess et al. (1984), and 9% lower energy requirements for depositing body protein as compared to NRC (1998). In validation, the model tended to underestimate the daily weight gain, feed intake, and the backfat probe thickness. While observations of swine growth and feed intake from validation data tended to have higher variation, the simulation result did not present the same variation as shown in observation. The estimation of the feed intake and weight gain was more accurate than the backfat probe thickness. The limitations of the modified simple pig growth model (MSPGM) need to be addressed when applying the model.

Second, a dynamic swine growth-swine barn operation model was proposed and applied to determine the importance of barn management based on the sensitivity analysis. The model results showed the importance of protein level in the diet, the setpoint temperature, and minimum body protein to lipid ratio (*minLP*) for all the swine production performance indicators. Based on the model, leaner swine performed better for the average daily gain (ADG) and feed conversion ratio (FCR). The sensitivity analysis results suggest feeding a sufficient protein diet, especially in the cooling season, to prevent the higher FCR. Moreover, the predicted results from the model imply that an optimum level protein diet is beneficial for the ADG in both seasons. Based on the results of the sensitivity analysis, this research found a positive trend between setpoint temperature and the FCR in the heating season. This demonstrates the potential to manage the FCR by controlling the setpoint temperature.

Third, scenarios for different evaporative cooling pad (ECP) operation offset (difference between indoor and setpoint temperature) were discussed. To better evaluate the ECP operation strategy at Ames, Iowa, 18-year historical weather data was applied for the ECP offset operation evaluation. Based on the proposed dynamic system model, the current research suggests the ECP control offsets for grow-finish swine mechanical ventilated swine barn with regard to indicators such as the ADG, FCR, marginal utility cost (MUC), and average daily profit (ADP). There was **no** statistically significant difference found for the FCR among the different scenarios; however, statistically significant differences in utility costs were found between the scenarios with a lower ECP operating temperature offset and higher offset, in addition to without ECP operation scenarios. This research also found a larger deviation for the ADP when the ECP operated at a higher ECP temperature offset or without ECP operation. Simulation results imply the potential benefits of operating the ECP at a lower temperature offset to reduce heat stress risk for the ADG and ADP. On the other hand, the simulation result also imply that contract growers who focus more on the MUC would choose not to operate a cooling pad under conditions discussed.

Finally, an indoor setpoint optimization procedure for swine was developed to optimize the entire growing cycle's swine production performance based on the proposed dynamic swine production system model. The procedure defined different objective functions to represent different parties in the industry: 1) to minimize the feed conversion ratio (FCR) for integrated producers, 2) to minimize the marginal utility cost (MUC) for contract growers, and 3) to optimize the daily profit (DP) for independent producers. A simulation case study was conducted in Ames, Iowa, in 2013 with different objectives to evaluate the optimization procedure. The results showed a higher setpoint temperature in the cooling season and longer growing period with regard to minimizing the marginal utility cost for contractors. Integrators and independent producers tend to meet the setpoint with a low critical temperature (LCT) to create the best feed conversion ratio and maximum average daily gain to produce revenue. While the optimized setpoint temperature profiles are similar for both with or without the evaporative cooling pad (ECP) operation, the setpoint tended to be higher for scenarios without an ECP, due to the difficulties to achieve the LCT. While contract producers and independent/integrated producers have different optimum setpoint temperature profiles, a setpoint temperature profile in between these has the potential to reduce the MUC while not affecting the FCR.

7.2 Recommendations

Based on results of this study, the following recommendations are made for future research on model development/application and swine production system experiments:

1. Model development and application for modern swine

Although swine models have been widely applied for different purposes, only a few studies calibrate/validate the model with more recent data to present potential modern swine growth. The current study has observed that swine in 2016 experiments grow faster, leaner, and are more efficient with higher feed intake. These modern swine growth patterns are different than older data published when most of the models were developed. Without calibration of the swine growth model, the anticipated results might be biased based on old data. The validation process, moreover, is necessary to understand the limitations of the model. A better understanding of the model limitations is necessary to appropriately apply the model.

The calibration process alone is not able to estimate all parameters to evaluate modern swine growth performance. Although the calibration/validation process could imply some parameters for modern swine growth performance, the trained parameters were fitted in the current study based on limited data under specific modeling schemes. Because only a few parameters in the nutrient partitioning scheme have been updated, there is an over-fitting concern when calibrating a large amount of parameters. There is a need to update the parameters for each experiment in the nutrient partitioning scheme to better evaluate modern swine growth performance. Fundamental research, such as energy usage efficiency in swine and minimum body lipid to protein ratio, are required to fill the gap between the current nutrient scheme and modern swine growth performance.

Based on the proposed modeling scheme, the swine growth performance prediction in a lower temperature range is not consistent with the observation results. To better understand swine growth in different environments, more experiments, for example, to examine lower critical temperature, critical thermal humidity index, metabolic performance in different environments, and feed intake under different environmental conditions, are needed to address genomic factors in environmental performance.

2. Barn Management suggestions based on the computer simulation

Although the proposed system model shows the capability of suggesting and estimating swine production performance under different barn management, the suggestion is limited by the system model assumptions. All suggestions based on the system model results should be taken as an academic discussion under certain conditions. Real situations outside of the model capability, such as disease, competition, and behavior change, may have critical effects on swine production performance. Although a physical system evaluation requires more resources, it is still important to verify the model-based suggestion/management based on physical experiments. Several follow up experiments are suggested for the model application proposed in this dissertation.

For Chapter 4, experiments with different protein level diets, different indoor setpoint temperatures, and different breeding lines of swine, are suggested to verify the swine growth performance direction demonstrated by the sensitivity analysis ensemble approach. The proposed experiment will require a large amount of observation to capture the average performance and to compensate for individual variability. In Chapter 5, the use of two individual rooms with different ECP control offsets for the same growing period is suggested in future research to demonstrate an evaluation of the model result. In Chapter 6, experiments that compared the control group (traditional setpoint based on industry recommendation) and the experiment group (optimum setpoint temperature for different perspectives) with the same outdoor temperature could demonstrate the value for the optimum scheme directly.

Barn management suggestions based on simulation results may not be consistent with the experiment. The discrepancy of the results will demonstrate the gap between the model knowledge and the actual situation. More research should be done to understand the discrepancies and to fill the gap between observations and our current understanding of the system.

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APPENDIX A: MSPGM MODEL

Based on the general scheme of nutrient partitioning proposed by De Lange(1995) and Moughan et al.(1987)**,** the model proposed by this study aims to estimate final body weight on a daily basis. With initial body weight (W_0, kg), initial protein weight (P_0) and initial body lipid to body protein ratio (*InitialLP*), the initial lipid weight (L_{int}) is:

$$L_{int} = InitialLP \times P_0 \quad \text{(A.1)}$$

where InitialLP can be described by Maximum daily protein deposition rate (Pd_{max} , g) and initial body weight (W_0, kg) based on NRC (2012):

$$Initial\ LP = (\ 0.305 - 0.00875 \times Pd_{Max}) \times W_0^{0.45} \quad \text{(A.2)}$$

Initial empty body weight (WE_0, kg) is calculated as the sum of initial protein weight (P_0, kg), initial lipid weight (L_0, kg), initial body water weight (Wt_0, kg), and initial body ash weight (A_0, kg):

$$WE_0 = P_0 + L_0 + Wt_0 + A_0 \quad \text{(A.3)}$$

where

$$Wt_0 = (4.332 + 0.0044 \times Pd_{max}) \times P_0^{0.855} \quad \text{(A.4)}$$

$$A_0 = 0.189 \times P_0 \quad \text{(A.5)}$$

Gut fill is predicted by equation

$$Gut\ fill = 0.3043 \times WE_0^{0.5977} \quad \text{(A.6)}$$

Total initial weight W_0 is

$$W_0 = WE_0 + Gut\ fill \quad \text{(A.7)}$$

The reference voluntary daily metabolizable energy intake (*MEvi*, kJ d^{-1}) is given as a function of body weight (*W*, kg) as modified by Schinckel et al. (2012) equations. This paper introduces a modification factor (M_{FI}) to Schinckel et al. (2012) equations in order to increase the flexibility as follows:

$$MEvi = M_{FI} \times a(1 - e^{-e^{b} \times W^{c}}) \quad \text{(A.8)}$$

where W is the pig live weight, a and b are constants that affects ME intake. Constants a, b, and c are different across general swine, gilts, and barrows as shown in Table A.1.

Table A.1 Constants for metabolizable energy intake estimation

Type of Swine	*a*	*b*	*c*
Gilts	46400.56	-3.666	0.9089
Barrows	46024.00	-5.077	1.320

To represent the impact of environmental temperature on metabolizable energy intake, the lower critical temperature (*LCT*) is estimated and *MEvi* is adjusted based on NRC(2012).

$$LCT = 17.9 - 0.0375 \times W \quad \text{(A.9)}$$

$$Fraction\ of\ MEvi\ intake = 1 - 0.012914 \times [T_i - (LCT + 3)]$$
$$-0.001179 \times [T_i - (LCT + 3)]^2$$

where the T_i is the indoor temperature in °C.

While the SPGM uses a fixed maximum protein deposition rate (Pd_{max}), this study assumes different Pd_{max} with different pig live weight based on linear interpolations from referenced Pd_{max} (Pd^{R}_{max}) published in NRC(2012) as shown in Figure 3.2. However, because different genotype of swine might have different Pd_{max} curve, this study assumes a Pd_{max} as

$$P_{dmax} = rPd_{max} \times Pd^{R}_{max} \quad \text{(A.10)}$$

where rP_{dmax} is the ratio to reference maximum daily protein deposition rate

Feed intake (F, g/d) is calculated by metabolizable energy of diet content (*MEd*, kJ/g).

$$F = MEvi/MEd \quad \text{(A.11)}$$

Swine feed usage is correlated to feed intake by assuming voluntary daily feed intake rate (F%vi, %)

$$F_{usage} = MEvi/MEd \div (F\%vi/100) \quad \text{(A.12)}$$

This model proposed by the current study assumes voluntary daily feed intake rate is 90%.

With the dietary amino acid (*AAd*, g/kg) and apparent amino acid availabilities (*AAa*, g/kg) for different kinds of amino acids (lysine, methionine, methionine plus cysteine, threonine, tryptophan, and isoleucine), the available amino acid intake (*AAAi*, g/d) is calculated:

$$AAAi = F \times \frac{AAd}{1000} \times AAa \tag{A.13}$$

The intake of available total protein (APi, g/d) is calculated in a similar way from the total dietary protein content (*AApd*). Protein-free metabolizable energy intake ($EPFi$, kJ/d) is calculated by gross energy content of protein (*EP*), which is assumed to be 23.6kJ/g

$$EPFi = F \times MEd - APi \times Ep \tag{A.14}$$

The maintenance requirement for total protein (*Pm*) or an amino acid (AAm, g/d) has priority over the total protein or amino acid demands for growth. The relationship between *Pm*, *AAm*, and body weight is given from metabolic rate:

$$Pm = 0.9375W^{0.75} \tag{A.15}$$

$$AAm = Pm \times (AA\%bp/100) \tag{A.16}$$

where *AA%bp* is the amino acid content of balanced ('ideal') protein (%) for different kinds of amino acids. The amino acid composition of balanced protein is 7.1% of lysine, 1.98% of methionine, 2.97 % of methionine plus cysteine, 3.77% of threonine, 0.91% of tryptophan, and 3.61% isoleucine)

The amount of total protein that can be used for gain (*Pg*, g/d), and amino acid that are available for gain (*AAg*, g/d) with absorptive efficiency of utilizing protein and amino acid at 85% are:

$$Pg = (APi - Pm) \times 0.85 \tag{A.17}$$

$$AAg = (AAAi - AAm) \times 0.85 \tag{A.18}$$

The amount of balanced protein that can be derived from each amino acid and that can potentially be utilized for growth (*BP(AA)g* (g/d)) are calculated:

$$BP(AA)g = AAg/(AA\%bp/100) \tag{A.19}$$

The actual amount of balanced protein that can be utilized for body protein deposition (BPg, g/d) is equal to the smallest quantity of balanced protein that can potentially be utilized for growth and that is supplied by each individual amino acid or total protein.

The potential body protein deposition rate (Pd_{pot}, g/d) is determined by *BP(AA)g*, *BPg* or the animal's upper limit to body protein retention (Pd_{max}, g/d), which is affected by pig gender, body live weight, strain, and breed.

$$Pd_{pot} = min[BP(AA)g, Pg, Pd_{max}] \tag{A.20}$$

With the supply of energy and amino acid, the model proposed by the current study can determine whether the potential body protein deposition rate equals the actual body protein deposit rate. Energy derived from amino acids and unbalanced amino acids that are inevitably catabolized (*E1*) is calculated as:

$$E1 = (APi - Pm - BPg) \times 11.5 \tag{A.21}$$

Energy derived from balanced protein that can be utilized for growth but that is supplied in excess of that required to support the potential body protein deposition rate

$$E2 = \left(BPg - Pd_{pot}\right) \times 11.5 \tag{A.22}$$

The amount of energy that is available for growth (Eg, kJ/d) is then calculated

$$Eg = EPFi + E1 + E2 + \left(Pd_{pot} \times Ep\right) - Em \tag{A.23}$$

Em (kJ/d) represents the maintenance energy requirements. In cold weather conditions, *Em* will be higher due to the needs of thermogenesis (NRC, 2012). If the temperature is higher than *LCT*, there is no thermogenesis. If the temperature is lower than *LCT*, the relationship in Eq. (A.26) takes place:

$$Em = standard\ Em + Em\ for\ thermogenesis \tag{A.24}$$

$$Standard\ Em = 824.248 \times W^{0.60} \tag{A.25}$$

$$Em\ for\ thermogenesis = 0.07425 \times (LCT - T) \times Standard\ Em \tag{A.26}$$

The potential body lipid deposition rate (Ld_{pot}, g/d) is then calculated:

$$\mathrm{Ld_{pot}} = (\mathrm{Eg} - \mathrm{Epd} \times \mathrm{Pd_{pot}})/\mathrm{Eld} \tag{A.27}$$

where *Epd* is the energy cost of body protein deposition (kJ/g) and body lipid deposition (kJ/g). In order to generalize the energy cost of body and lipid deposition. Eq. (A.28) shows *Epd* and *Eld* modified by a ratio independently:

$$Epd = rEpd \times 44.35\ kJ\ g^{-1} \tag{A.28}$$

$$Eld = rEld \times 52.3\ kJ\ g^{-1}$$

The final protein and lipid weight are then calculated:

$$Pf_{pot} = P_0 + Pd_{pot}/1000 \tag{A.29}$$

$$Lf_{pot} = L_0 + Ld_{pot}/1000$$

Because SPGM assumed a minimum lipid/protein ratio (*minLP*), this study assumes *minLP* is equal to $InitialLP$. If $Ld_{pot} < minLP \times Pf_{pot}$, the protein deposit will be reduced by

$$Pd_{red} = \frac{1000(minLP \times Pf_{pot} - Lf_{pot})}{\frac{Epd - Epe}{Eld} + minLP} \tag{A.30}$$

The lipid deposition will be increased by

$$Ld_{incr} = Pd_{red} \times \frac{Epd - Epe}{Eld} \tag{A.31}$$

where the *Epe* is the energy cost for protein extrusion. *Epe* assumes to be 12.1kJ/g based on De Lange et al. (1995)

The final protein and lipid deposition will be described by

$$P_f = P_0 + \frac{Pd - Pd_{red}}{1000} \tag{A.32}$$

$$L_f = L_0 + \frac{Ld + Ld_{inc}}{1000}$$

With the relationship between water, ash weight, and protein weight, the final body weight is calculated:

$$W_f = P_f + L_f + W_{tf} + A_f \tag{A.33}$$

Weight gain (*WG*) equals $W_f - W_0$

The MSPGM requires amino acid content for estimating balanced amino acid intake. All diet information is based on Experiments shown in Table 3.2 a) to Table 3.2 c)

APPENDIX B: SWINE BARN DIMENSION AND VENTILATION DESIGN

The current research designed the double wide swine barn to grow overall heads of grow-finish swine with mechanical ventilation system. The swine barn is designed with a ceiling to avoid heat loss in the heating season and heat gain in the cooling season. To represent large scale industry swine barn set up, the barn is assumed to be double-wide and have two rooms for grow-finish operation. The dimensions and designs are as shown in Figure B.1. The wall is constructed based on concrete walls and wood walls. There is a concrete wall designed to separate two individual rooms; however, the current study assumed both rooms are operated at the same schedule to simplify the calculation to better address sensitivity analysis in chapter 4. To ensure each pig has approximately 8 sq. ft. per pig including aisles and area for facilities, the swine barn floor plan area is designed as shown in Figure B.2.

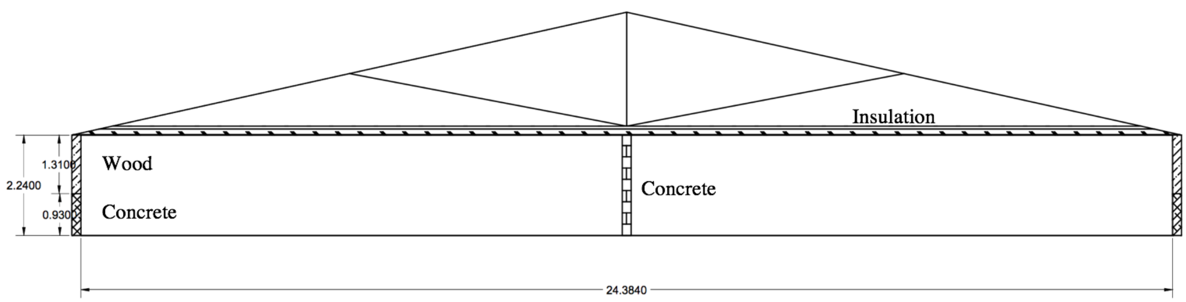

Figure B. 1. Dimension and material for the swine barn in meters

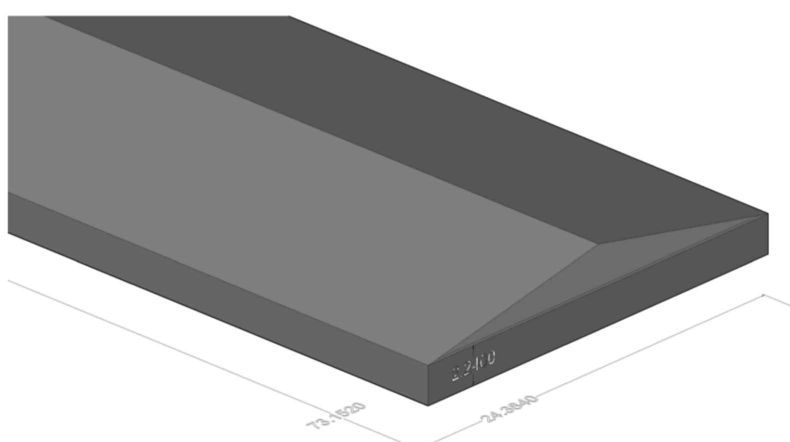

Figure B. 2. Dimension for the swine barn in meters

Details for thermal properties and heat conductance are listed in Table B.1.

Table B.1 Construction material of building components

	Materials	Thermal transmittance through conduction (W/ m^2-K)	Thermal resistance (m^2-K/W)	Total Thermal transmission: U (W/ m^2-K)
Wall	ho	22.7	0.04	0.476
	Wood Walls		2.20	
	Concrete Walls		0.14	
	hi	0.57	1.75	
Ceiling	ho	0.57	1.75	0.122
	Fiberglass insulation		4.69	
	hi	0.57	1.75	

Concrete walls are designed to be 4" concrete masonry unit, and wood walls are designed to be two 1" plywood with R-10 insulation. The ceiling is assumed to be insulated with approximate R-26 insulation. Based on Table B.1, Table B. 2 shows the overall heat conductance with designed swine barn dimension.

Table B. 2 Calculated UA-value for growing to finishing swine building

Building construction	F	U-Value (W/ m^2-K)	Length (m)	Width (m)	Height (m)	Surface Area (m^2)	UA Value (W/ K)
Floor	1.4		73.15	24.38			273
North/south Wall		0.476	73.15		2.24	163.9	78.0
East/West Wall		0.476		24.38	2.24	54.62	26.0
Ceiling		0.122	73.15	24.38		1784	218

Based on overall UA value for each wall, the overall all heat conductance for the building envelope is as shown in eqn. B.1.

$$UA_{total} = F \times L + UA_{north} + UA_{south} + UA_{east} + UA_{west} = 699 \tag{B.1}$$

In the cooling season, the amount of the heat gain through the ceiling is relatively small compared to the heat gain from animals. In the heating season, the percentage of heat loss through the ceiling is relatively small compared to the heat loss through ventilation (Li, 2000). To simplify the thermal system model for simulation discussion, the attic temperature is assumed to be equal to the outdoor temperature.

For appropriate ventilation rate to supply swine barn, the current research designed minimum ventilation rate with 8.7 cfm per pig and maximum ventilation rate with 121.3 cfm per pig. The control offset and corresponding ventilation rate is as Table B.3. To make sure the double wide room has more control accuracy with lower offset, the proposed swine barn has more control stages with lower ventilation rate.

Table B.3 Stage control for ventilation fans and heaters

Heating/ Cooling	**Details of control stages**			
Ventilation system	Ventilation rate offset (°C)	Ventilation rate (m^3 s^{-1})	Size and Number of Fans	Average Ventilating Efficiency Ratio, VER (m^3 s^{-1} W^{-1})
	0	9.83	16" x 6	5.76 x 10^{-3}
	2	19.83	16" x 6 +36" x 2	7.66 x 10^{-3}
	4	29.84	16" x 6 +36" x 4	8.29 x 10^{-3}
	6	51.36	16" x 6 +36" x 4+48" x 2	8.65 x 10^{-3}
	8	94.40	16" x 6 +36" x 4+48" x 6	8.88 x 10^{-3}
	10	137.44	16" x 6 +36" x 4+48" x 10	8.97 x 10^{-3}
Heater	Heating rate offset	Heating rate (W)		
	0	0		
	-2	59 k		
	-4	118 k		
	-6	177 k		

In order to keep the cooling pad face velocity within the range (less than 4 m s^{-1}) from experiment conducted by Franco et al. (2010), the proposed system designed a 46.45 m^2 cooling pad as inlet for the ventilation system. Based on the proposed design, the estimated maximum ventilation rate will be around 3 m s^{-1}, which is less than the maximum air velocity in experiment held by Franco et al. (2010).